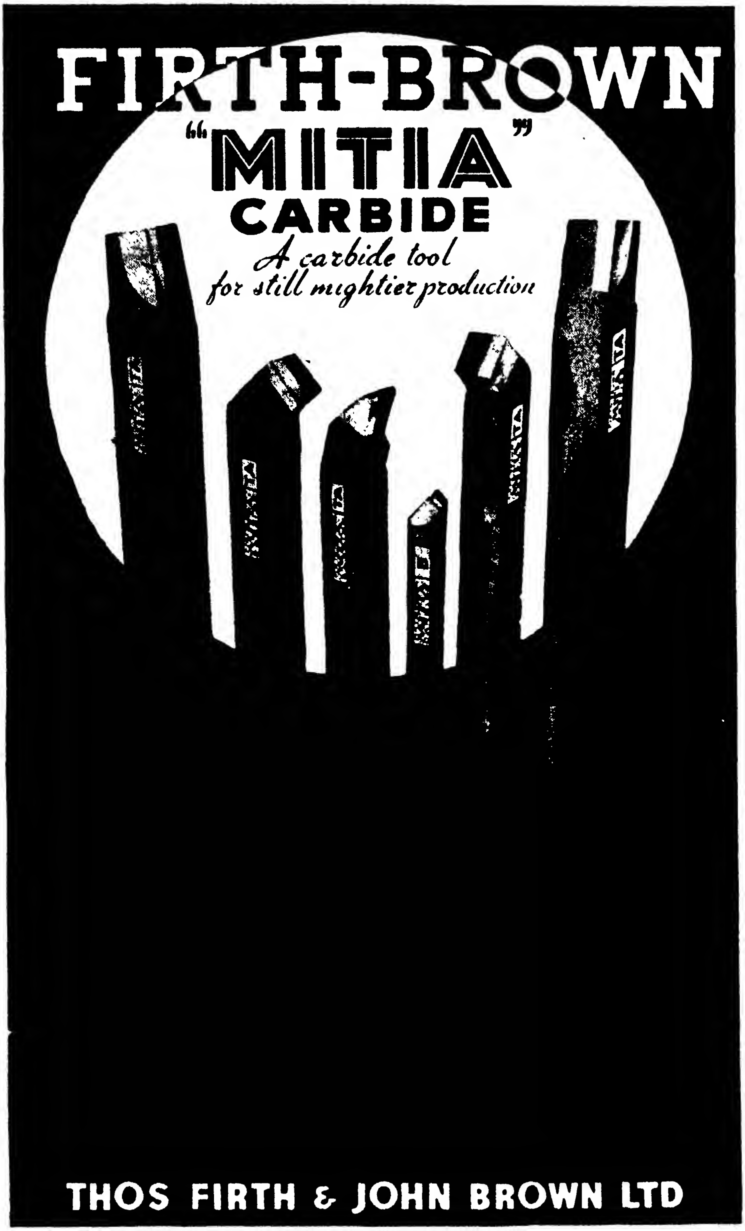

ENGINEERING INSPECTION

AN INTRODUCTION TO INSPECTION WORK INCLUDING SPECIAL REFERENCE TO AERO REQUIREMENTS

BY
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"ENGINEERING WORKSHOP DRAWING," "A FIRST YEAR ENGINEERING DRAWING"
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"BLUEPRINT READING SIMPLIFIED"
"SCREW THREAD CUTTING AND MEASUREMENT," ETC.
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PREFACE

It may be considered platitudinous to remark that an outstanding feature of recent industrial development is the rising status of the Inspection Department. Intensified production to close limits in large engineering concerns engaged in interchangeable manufacture has swelled the numbers of inspectors, viewers, gaugers, examiners, etc., to an extent truly amazing. In one great London engineering works, for instance, no less than one workshop employee in five is concerned with inspection, and now that "process inspection" has become so thoroughly organized in connexion with vitally important Government work in factories all over the country, the demand for intelligent inspection workers, from the humblest gauger to the most responsible and highly skilled inspection expert, shows no signs of abatement.

To write a short book, designedly popular and interesting in character, likely to prove useful to workers so diverse in previous training and qualifications and who, while engaged in the same great industry may yet be concerned with the manufacture of totally dissimilar objects, has presented a problem. The method adopted, after much consideration and long experience in training students for usefulness in engineering, involves commencing from general principles in an effort, so far as exigencies of space permit, to explain the relative position of the Inspection Department in the general organization and economy of a large works. Thence onward the method involves finding common ground, discovering an L.C.M. of basically important facets of the work, a knowledge of which is likely to increase the usefulness of a great number of intelligent inspection workers by widening their engineering consciousness, so enabling a more knowledgeable approach to daily tasks and problems. In furnishing fundamental technical guidance the book should assist many who. in furtherance of the great national rearming effort, have entered industry without previous technical experience.

With these aims in mind, an attempt has been made to provide clear information on such important selected phases of the work as the meanings of limits and tolerances, modern materials—with special emphasis on materials largely used in aircraft work—mechanical testing, heat treatment and hardness testing, measuring and gauging methods and devices, both for tool-room and mass-production purposes, etc.

Readers particularly interested in inspection of aircraft and aero engines will find it useful to refer to the specialized well-illustrated books in Pitman's Ground Engineers' Series. Among these is *Aero Engines* (*Inspection During Manufacture, Overhaul and Test*), by A. N. Barrett, A.M.I.A.E., A.F.R.Ae.S. In compiling the aero-inspection notes in this book frequent references have been made to Mr. Barrett's useful and popular book (recognized by the Air Ministry) and, by permission of Publisher and Author, courteously and readily granted, reproductions of illustrations, typical specifications, etc., have been made in order to enhance the usefulness and interest of this volume, which is framed on more general lines.

Throughout the book frequent references are made to relevant British Standard Specifications, a complete list of which can be obtained post free from the British Standards Institution, 28 Victoria Street, London, S.W.1, also to D.T.D. (Directorate of Technical Development) Specifications, a complete list of which can be obtained from His Majesty's Stationery Office, Kingsway, London, W.C.2. In addition there will be found many references to "Inspection Leaflets." These will be found in the *Airworthiness Handbook* (A.P. 1208).

Inspectors engaged on work of high precision in connexion with plain or screwed gauges are strongly recommended to consult *Notes on Screw Gauges* (4s. 6d. net) and *Notes on Gauge Making and Measurement* (2s. net). Both are well illustrated and have been compiled by the Metrology Dept. of the National Physical Laboratory. The latter contains a short list of technical publications of interest to gauge makers. They may be obtained direct from H.M.S.O., Kingsway, London, W.C.2, or by ordering through any bookseller.

Thanks are due to a number of engineering firms who have generously assisted by lending blocks and supplying technical information. Individual acknowledgments are paid in the text.

It is no doubt a vain hope that a book containing so many detailed references is entirely free from errors, and I shall be grateful if any such are pointed out to me. Letters addressed to me c/o Sir Isaac Pitman & Sons, Ltd., Parker Street, Kingsway, London, W.C.2, are promptly forwarded.

A. C. P.

CONTENTS

CHAPTER VI

CHAPTER VII

CHAPTER VIII

CHAPTER IX

CHAPTER X

CHAPTER XI

CHAPTER XII

Some British Standard Specifications Useful to Inspectors, Gauge Makers, etc.

No. 21—B.S. Pipe Threads, Part I, Basic Sizes.
,, 84—B.S. Screw Threads of Whitworth Form.
,, 93—British Association Screw Threads.
,, 164—Limits and Fits for Engineering.
,, 817—Cast Iron Surface Plates and Tables.
,, 818—Cast Iron Straightedges.
,, 852—Toolmakers' Straightedges.
,, 869—Toolmakers' Flats and High Precision Surface Plates.
,, 870—Micrometers (External).
,, 887—Vernier Callipers.
,, 888—Slip (or Block) Gauges and their Accessories.
,, 906—Engineers' Parallels (Steel).
,, 907—Dial Gauges for Linear Measurements.
,, 917—Screw Thread Gauge Tolerances.
,, 957—Feeler Gauges.
,, 958—Precision Levels for Engineering Workshops.
,, 959—Internal Micrometers.
,, 969—Tolerances for Plain Limit Gauges.
, 1044—Designs for Plug, Ring and Gap Gauges.

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ENGINEERING INSPECTION

CHAPTER I

THE INSPECTION DEPARTMENT. AN INTRODUCTION TO ITS SCOPE AND FUNCTIONS

PRACTICALLY all engineering factories now have an inspection department which, if efficiently organized and controlled, proves an aid to production as well as a check upon the accuracy and conformity to specification of the work produced. We shall see later that this is by no means a complete definition of the function and usefulness of inspection, the scope of which necessarily varies according to the nature of the business.

The Status of the Inspector. Inspection, planning, progress work, time and motion study, and to some extent the drawing office as now known, are comparatively new departures in engineering, having arrived at their present importance as mass-production methods have become so generally established. Consequently there has been a good deal of improvised organization, not only in the separate internal work of these and other newer departments, but also in regard to their relationships one with another and to the management.

In the organization of an inspection department *substantial independence of control* is a primary essential, yet at the same time effective correlation with the rest of the works' departments, including the sales department, must be maintained. The status of the Chief Inspector in a large works is high; in fact an outstanding feature of recent industrial development is the rising status of the Inspection Department. His inspection rooms are often scattered throughout the works, each being in the charge of a man responsible only to his chief but having a standing sufficiently high to maintain suitable relationship with those responsible for shop production, viz. foremen, underforemen, etc.

Anyone with executive experience in the engineering industry will be aware of the difficulties encountered in inspection work when the Chief Inspector is subservient to an official whose chief preoccupation is output. The matter has been arranged in some large undertakings where the Works Manager, perhaps called Works Superintendent, controls the whole of the organization (productive, technical, and commercial) by making the Chief Inspector directly responsible to him. In this arrangement the Chief Inspector and the other small band of senior executive officers directly responsible to the Works Manager may form a Management Board. Under this scheme of organization the Chief Foreman and Chief Inspector have equal status. In other cases the Chief Inspector is placed under the control of someone else, perhaps the Chief Foreman, an anomalous arrangement which may possibly work satisfactorily, but in view of the fact that the Chief Foreman is ultimately concerned with *production*, necessarily contains the seeds of difficulty.

Another arrangement is to make the Chief Inspector responsible to the Works Engineer. The functions and responsibilities of the latter official vary in different factories. He may be concerned wholly with the plant; he may also have charge of design and drawing offices. In the latter case defects due to errors in design and drawing may not receive that measure of independent criticism they would otherwise receive from the Inspection Department. Much has been written on this theme, but we need enlarge no further upon it in this short volume, contenting ourselves with stressing the generally accepted principle that the Inspection Department should be as far as possible independent, so that the Chief Inspector may preserve his free judgment unprejudiced by lack of status and by uncertainty as to the measure of support he would receive when difficulties arise—as indeed they must from time to time—over rejected work. Final appeals against the Chief Inspector's judgment can then be made to a senior executive not mainly interested in the shops, perhaps the Works Manager, the Progress Manager, or even the Secretary.

The Scope of Inspection. Inspection, to be comprehensive, should be concerned with everything entering and leaving the factory. To inspect a finished assembly only to find that the material employed was totally unsatisfactory would obviously not be sound economics. Inspection therefore must start at the beginning. The raw materials should pass through the Inspection Department *en route* to the stores, and inspection should continue until the completed work is finally ready for dispatch to the customer.

The Air Ministry insist that the value of inspection depends not only upon the skill and care with which inspection is performed, but on every detail and assembly being followed through *from the raw material to the finished product.*

The Inspection Department is mainly concerned with—

1. Raw materials (these may comprise castings, forgings, pressings, bar material, sheets, etc.);
2. Partly manufactured or finished parts bought out;
3. Machining and other manufacturing operations during production (including heat treatment, etc.);
4. Sub-assemblies;
5. Final erection.

1. Raw Materials. When considering raw materials it is well to remember that the raw materials of one works often comprise the finished product of another. Thus a firm turning out castings as finished products will count ingots and pigs among its raw materials. A firm turning out a range of bolts, nuts, screws, etc., will consider bar metal its raw material—whereas to the bar makers ingots, etc., comprise raw material.

The inspection of raw materials is usually made in reference to the specifications to which they are ordered and supplied, and its nature will be decided by the nature of the service expected from the parts to be manufactured. In the case of *bar metal* it should be examined as soon after receipt as possible. Reference must first be made to the specification, requisition, or order sent by the Purchasing Department, as this will refer to quantity, size, quality, weight, limits of accuracy, mechanical properties, finish, etc. Firstly, dimensions will be checked. On bright drawn bar, possibly ordered to suit standard collets, the tolerances will be comparatively small; whereas for other purposes commercial bar may have been ordered, and a high degree of exactitude in dimensions will certainly not be expected. Then, too, it will be necessary to examine for surface defects, e.g. cracks, seams, flaws, etc.

It should be added that the importance of efficient material inspection has grown with the increased use of automatic and high-speed machine tools, because high output multiplies the losses likely to occur if defects, undiscovered before machining, reveal themselves after manufacturing processes have been undertaken. In some cases it may be necessary to conduct tests on raw materials to determine their mechanical, physical, or chemical qualities. Tests of this kind are usually made by the Experimental or Research Department on numbered samples submitted by the inspector. Similar in character to the testing of bar material is the testing of sheet metal. In many cases it will be necessary to apply the tests stipulated in B.S.I. or A.I.D. Specifications, Inspection Leaflets, etc.

The Air Ministry instruction is: "*All materials used in the construction of aircraft shall be in accordance with the specifications approved . . . and every batch shall be proved to comply with such specification by suitable examination, sampling and testing by approved methods.*"

Material received at an aero works must be placed in a "bonded store" as soon as the inspector has correlated it with the release note or other evidence of prior inspection. If for any reason this evidence is missing, the material must be held in "quarantine store" until either the release note or its equivalent has come to hand or the material has been completely reinspected.

INSPECTION OF CASTINGS. This requires specialized skill. Steel castings, for instance, are turned out with much greater success now than formerly. The more efficient steel foundries often maintain their own Inspection Department independent of the production staff. Usually the inspectors report directly to a director or manager of the firm. In this way a check is kept on faulty production. A record of every casting made from each cast of steel supplied to the foundry is kept, and as each heat is analysed day by day, it is easy to trace, and possibly scrap, during the early stages of manufacture, any castings not conforming to specification. An expert inspector also examines castings before dispatch to the customer in order to ensure their correctness generally. Magnetic tests and X-rays may possibly be used to detect internal flaws in steel castings and welded parts, but these methods at present are only applicable to castings relatively thin in section.

2. Partly Manufactured or Finished Parts Bought Out. These are passed through the Inspection Department for tests which will, of course, have relation to drawings and specifications, indeed in some cases gauges also, sent to the supplying firm or sub-contractor. The inspector's report must always be concise, i.e. "briefly to the point," as well as being unequivocally decisive as to the quantity of parts, the general workmanship, conformity to specification, etc.

A typical *Air Ministry requirement* is that the constructor shall ensure that all components and parts obtained from sub-contractors have been inspected and approved in a manner officially laid down.

3. Inspection of Machining Operations or of Partly Manufactured Parts. This is a big undertaking, especially, for instance, where batteries of automatic or semi-automatic machines are installed. Indeed in this side of inspection work more employment is found than in any other. As in all branches of inspection, the testing must be based on the requirements of the factory and the design and purpose of the product. It has been said that the ideal for parts manufactured in the works is inspection and stamping (on work or accompanying labels or record books) after every operation—a method which obviates the wastefulness of performing further operations on parts previously spoiled by incorrect machining. This naturally proves very expensive, requires a very large inspection staff, and sometimes causes delays. At the same time it will be clear that losses due to lack of inspection and subsequent discovery of errors will be cumulative in the case of mass-produced parts requiring many operations. Hard-and-fast rules cannot be laid down, because inspection is, and must be, relative to the type of factory, class, and function of the product, the cost of the minimum inspection considered necessary, etc. In some shops the whole of one batch of machined details passes to the Shop Inspection Department after every operation. This, of course, is facilitated if the parts are small and easily portable; in others the inspectors visit the machines and check the products while machining is in progress. This enables the early detection of errors. In fact it is the general rule in some shops for the inspector to check over the first few pieces from every set-up, thereafter keeping an eye on the output more or less continuously. The smaller the tolerances the more frequent must be the inspection, not only of the product but of the workshop gauges also.

As an example many readers will be aware that in peace time the inspection of great quantities of Government "stores," apart from aircraft work, is undertaken at one or two central inspection depots, but that on the outbreak of war the work is largely decentralized by the establishment of local administrative offices in various great provincial centres from which the local inspection of stores can be organized, travelling inspectors being dispatched for long or short periods to the contractors' works, where they are enabled to watch processes as well as products and to save an enormous amount of time.

Of course, the special requirements and circumstances attending the inspection of aero materials, e.g. engines, airframes, components, etc., were met by the organization of the A.I.D. which functions under what must assuredly be the most comprehensive, lucid, and efficient inspection scheme in existence.

The *Air Ministry* stipulate that the constructor should maintain an *efficient process inspection* and record the progress of such *inspection for each component.* Every component must be finally inspected and approved by a qualified member of his inspection staff, who must stamp the component in such a way that he can afterwards be identified as the person responsible. Certification by A.I.D. inspectors is only given after they are fully satisfied that *each operation in the complete series has been performed efficiently.*

4. Inspection of Sub-assemblies. The inspector first satisfies himself that the components have all passed through the department, which leaves him free to concentrate on the results of fitting and assembling operations. If the assembly is adversely affected by one or more components, it becomes necessary to look into the inspection records of these. Generally, however, the inspector is able to concentrate on the assembled unit as a whole. The inspector of sub-assemblies soon becomes conscious of the great value of adequate inspection of components during production. It eliminates much hand work and fitting during assembly and facilitates the inspection of sub-assemblies.

5. Inspection of Final Erection. The same general procedure is followed as in the inspection of sub-assemblies. Details and components will all have been assembled previously, so that the inspector is free to concentrate on the results of assembling and erecting work. Special classes of fits may have been specified, and attention to these is essential. If the job is for dispatch, it is necessary to ensure that all loose accessories are present, and, finally, that the general external appearance of the whole, e.g. painting, finishing, polishing, etc., is up to the requisite standard.

Inspectors' Stamps. An inspector is provided with stamps for marking the materials or articles which he examines. These enable the identity of the inspector to be ascertained and signify his approval as satisfactory of the articles stamped.

Before stamping an article the inspector must satisfy himself (1) that the materials conform to specification or drawing; (2) that the article is correct as to size and satisfactory as to finish; (3) the material has not been improperly treated and is free from defects; (4) that preceding operations have been inspected previously; (5) in the case of assemblies, that the parts have all previously passed inspection and are properly fitted and secured.

Inspection Leaflet No. 18 gives detailed instructions on inspection markings for both metal and timber parts. Readers engaged on aircraft inspection should consult this leaflet, which is illustrated and deals in detail with the position of inspection markings on the whole range of aircraft parts. Then, too, in *Inspection Leaflet No.* 128 directions are given regarding the position and nature of inspection approval marks on engine and engine accessory parts. Haphazard application of such marks might well cause concentration of stress, so enhancing the risk of failure from fatigue.

Standards of Inspection. Experienced inspectors, especially those with sound technical training and experience, are able to set themselves a right standard in relation to the circumstances in which the work will be used. Their knowledge of the uses of the parts they inspect enables them to do more than look for deviations from the ideal. These are sure to be found in any mass-produced batches of parts, and experience will enable the inspector to use discretion in aiming at efficiency and safety, yet disregarding departures from specification which would have no effect on ultimate performance. He has ample opportunities for co-operation with the foremen in correcting and improving standards of workmanship throughout production. He remembers that he is not mainly concerned with finding fault, but with safeguarding the firm from legitimate complaints by customers. Unnecessarily "particular" inspection may be just as detrimental to a firm's interests as careless inspection, and nothing can more readily mar interdepartmental good relations. Senior inspectors with a knowledge of welding, deposition, heat treatment, rectification, etc., find ample scope for co-operation with the Salvage Department in restoring parts to usefulness and so reducing debit charges due to scrap.

Specifications, Tolerances, and Gauges. The completeness of a specification tends towards more consistent quality, but adequate inspection is necessary if standards of quality are to be maintained. We shall see later that there is no such thing as the mass-production of components to exact size. Parts of supposedly identical size and shape produced in different shops vary slightly, but if workmanship is controlled by a practicable system of tolerances and gauges, we shall have *precision* work with negligible variations.

Tolerances are fully discussed in Chapter II. They allow for differences in dimensions prescribed in order to tolerate unavoidable errors in workmanship. *Gauges*, of course, are used to ascertain that no dimensions fall outside the tolerances specified on the drawings.

Gauges are discussed and described, within the space available in this short book, in Chapters VI–X. They are of many kinds, e.g.—

1. *For absolute direct measurements:* Verniers, micrometers, certain comparators, etc.
2. *Single-purpose gauges:* Plug, ring, snap, thread (outside and inside), templets, etc.
3. *Mechanical gauges:* Indicators, expanding plug gauges, amplifying gauges, etc.
4. *Optical gauges:* Magnifying, projecting.

In interchangeable manufacture a comprehensive gauging system is indispensable, ranging from simple plug, ring, and snap gauges of the "go and not go" type, which can be handled by juvenile or female labour, to elaborate comparator and indicator work calling for the intelligent skilled services of approved inspectors with a background of technical training.

Other Necessary Inspection. It must not be overlooked that in addition to the inspection of production parts the inspection of tools and similar accessories requires attention. In large concerns a *tool-inspection department* undertakes this work, but in smaller works the head of the tool-room often accepts responsibility. Inspection of tools comprises examination of (1) raw material (tool steels, etc.); (2) tools, jigs, etc., produced in the factory; (3) tools purchased outside (taps, dies, cutters, etc.). On approval the raw material can pass direct to the Tool Steel Store and the small tools, etc., to the Tool Store. The inspection of tools, jigs, etc., made in the factory will be done at various stages in their manufacture, e.g. end-milling cutters will probably be inspected after turning and after milling. Following this they are usually heat-treated, ground, and finally inspected as finished cutting tools. In order for it to be able to inspect raw materials and small tools purchased from outside it will be necessary for the Tool-inspection Department to be provided with a copy of the Purchasing Department's requisition.

Finally, there is an amount of miscellaneous inspection which should be delegated to employees having special knowledge and qualifications, e.g. new machines, machine-tool accessories, belting, etc., should be inspected by the Works Engineer's or Millwright's Department; lamps, cables, motors, etc., should be inspected by the Head Electrician; sundries such as cotton waste, etc., should be inspected by the Head Storekeeper. The inspecting official responsible should report in exactly the same way as a production inspector, so that the idea *inspection of everything* becomes a useful reality, no material of any description being accepted as correct unless the fact is made apparent through the medium of an inspector's report.

Inspection Records. Methods of reporting and recording vary from firm to firm. Payment often depends on the accuracy and time spent on producing the work. Whatever the method adopted, it should be of assistance to costing and statistical experts in tabulating the nature and percentage of defects.

The Aeronautical Inspection Directorate. (A.I.D.) This was created in 1913 as the War Office inspecting authority for aircraft. Later on, however, when the R.F.C. and R.N.A.S. amalgamated, the A.I.D. assumed sole authority, independently of the War Office, for British service aircraft. The gradual development of the system of "approval of firms' own inspection" was based on the policy of every firm carrying out its own inspection upon lines approved by the A.I.D. Approved inspectors, employed and paid by their own firms, actually take the place of A.I.D. inspectors in many cases.

CHAPTER II

LIMITS AND TOLERANCES

A HIGH degree of uniformity is essential in any product manufactured in large quantities, as without it *interchangeability* would be impossible. Tools, fixtures, jigs, and gauges are some of the mechanical devices used in engineering to obtain this condition. No two men do the same job in exactly the same way, and they therefore do not obtain exactly the same result—the elimination (or close control) of the difference between the two results is the aim of the draughtsman when he specifies the "limits" of the jig and tool and gauge designer, and subsequently of the skilled inspector.

It is manifestly impossible to produce *any two or more* components having mating dimensions *exactly* alike, even with the most efficient machinery obtainable. Therefore ranges of permissible differences in dimensions have been standardized under the name *limits*. In connexion with this word two further terms are used, viz. *tolerance* and *allowance*.

The word **tolerance** indicates that the machinist is not expected to produce interchangeable parts to absolute accuracy but is permitted *a small range of error.*

Tolerance has been defined *as a difference in dimensions prescribed in order to tolerate unavoidable imperfections in workmanship or machining.* The greater the tolerance which can be allowed, the more cheaply can the work be done.

Allowance is not quite the same thing. *It is a prescribed difference in dimensions in order to allow of different classes of fits.*

In a nutshell, then, *tolerance* is the margin of error allowed on dimensions so as to allow for reasonable inaccuracy in workmanship and appliances, while *allowance* is a difference in prescribed dimensions to allow of the desired class of fit.

Minimum allowance is the difference between the largest shaft and the smallest hole.

Maximum allowance is the difference between the smallest shaft and the largest hole.

Fig. 1 will help to make this clear.

Alternative Ways of Stating a Tolerance. (1) $1{\cdot}271'' \pm 0{\cdot}001$. Here we have the *nominal size* with the *tolerance* split both ways, i.e. plus and minus.

(2) $1{\cdot}270'' \begin{matrix} +\ 0{\cdot}002 \\ -\ 0{\cdot}000 \end{matrix}$. Here we have the *nominal size* with a positive allowance only.

(3) $\begin{matrix} 1{\cdot}272''\ \text{max.} \\ 1{\cdot}270''\ \text{min.} \end{matrix}$ Here the maximum and minimum *dimensions* are given as decimal fractions without a specific reference to *tolerances.*

To the draughtsman methods (1) and (2) are preferable, because they give *one* dimension, and in adding up figures and making other calculations he will use the dimension and disregard the tolerance. (See note below.)

In the workshop the third method is preferable, for we have a clearly stated maximum and minimum dimension. Work lying between these will be accepted, and mental subtraction is reduced, if not completely obviated.

Addition of Dimensions with Limits. The inspector may have to add a number of dimensions, and when these have plus and minus limits he must be careful not to confuse them. Thus he may have to add the following—

(*a*) $0{\cdot}600''\,{}^{+\,0{\cdot}0005}_{-\,0{\cdot}001}$ (*b*) $0{\cdot}325''\,{}^{+\,0{\cdot}0003}_{-\,0{\cdot}0002}$ (*c*) $0{\cdot}75''\,{}^{+\,0{\cdot}002}_{-\,0{\cdot}002}$

The addition of the nominal sizes = 1·675″
" " " " plus limits = 0·0028″
" " " " minus " = 0·0032″

Therefore total high and low limit dimensions are 1·6778″ and 1·6718″ respectively.

Subtraction of Dimensions with Limits. When subtracting two dimensions with limits, the *minimum difference* is found by subtracting the maximum limit of the smaller dimension from the minimum limit of the larger dimension. Conversely, the *maximum difference* is found by subtracting the minimum limit of the smaller dimension from the maximum limit of the larger dimension.

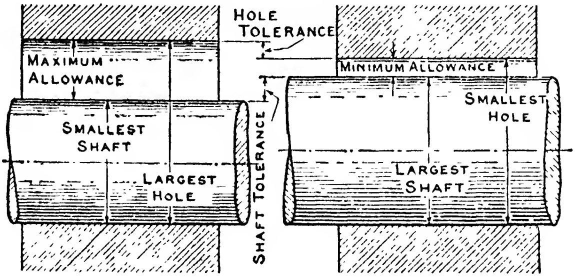


FIG. 1. TOLERANCES AND ALLOWANCES

Example. Subtract (*a*) $3{\cdot}752''\,{}^{+\,0{\cdot}006}_{-\,0{\cdot}004}$ from (*b*) $6{\cdot}528''\,{}^{+\,0{\cdot}002}_{-\,0{\cdot}005}$

1. The difference between the nominal dimensions is 6·528″ − 3·752″ = 2·776″.
2. To find the minimum and maximum difference—

Dimension (*a*) minimum length = 3·748″
maximum " = 3·758″
Dimension (*b*) minimum " = 6·523″
maximum " = 6·530″

Next subtract (*a*) from (*b*)—

(*b*) minimum 6·523″ (*b*) maximum 6·530″
(*a*) maximum 3·758″ (*a*) minimum 3·748″
2·765″ 2·782″

Thus the extreme differences between the limits are 2·765″ (minimum) and 2·782″ (maximum).

How Tolerances are Stated on Drawings. The nominal size is written first, followed by the upper and lower limits. If, for example, we take any dimension, say 1¼ in., and we wish that it shall not vary by more than ten thousandths of an inch above or below this figure, we write it thus: $1\tfrac{1}{4}''\,{}^{+\,0{\cdot}010}_{-\,0{\cdot}010}$

The actual dimensions which will then be acceptable will be anything between 1·510 in. and 1·490 in. These figures are called the upper and lower dimensions respectively and are obtained, of course, by adding the upper limit (+ 0·010 in.) to the 1½ in. dimension, giving 1·510 in., and subtracting the lower limit (− 0·010 in.), giving 1·490 in.

The dimension 1½ in. is called the nominal dimension; the figure preceded by the + sign is called the upper limit, and the one preceded by the − sign the lower limit. When the *lower dimension* is subtracted from the *upper dimension* we get the tolerance, in this case 0·020. In this instance we have "split the tolerance both ways." Note that the limit giving the higher or upper dimension should always appear above the limit giving the lower dimension.

Sometimes it will be found that the limits will be both + or even both −; for example, if we consider $2''\begin{smallmatrix}+\,0{\cdot}005\\+\,0{\cdot}001\end{smallmatrix}$ the dimensions may vary between 2·001 in. and 2·005. in.

But if we write $2''\begin{smallmatrix}-\,0{\cdot}001\\-\,0{\cdot}005\end{smallmatrix}$ the dimensions may vary between 1·995 and 1·999. Thus we see that the sign + or − tells us when to add and when to subtract to obtain the permissible range of the dimension. Note that the tolerance is in both cases 0·004 in. A little study of the following examples will make this clear.

(*a*)	1¼″	+ 0·008.	Upper dimension	1·258″	Tolerance 0·008″
		− 0·000.	Lower ,,	1·250″	
(*b*)	5⅛″	− 0·020.	Upper ,,	5·105″	Tolerance 0·04″
		− 0·060.	Lower ,,	5·065″	
(*c*)	½″	+ 0·0012.	Upper ,,	0·5012″	Tolerance 0·0022″
		− 0·001.	Lower ,,	0·499″	
(*d*)	¼″	− 0·001.	Upper ,,	0·249″	Tolerance 0·001″
		− 0·002.	Lower ,,	0·248″	
(*e*)	1⅞″	+ 0·004.	Upper ,,	1·879″	Tolerance 0·0015″
		+ 0·0025.	Lower ,,	1·8775″	

The Newall System of Limits. Four classes of fits are provided for in the Newall system, applying to fits between shafts and their holes. In the B.S.I. system three principal classes of fits are recommended. The following remarks apply to the Newall system: (1) **Force fits** (*F*), in which the shafts have to be forced into their holes by hydraulic pressure, or the holes have to be expanded with heat to embrace the shafts; (2) **Driving fits** (*D*), in which the shafts have to be driven into their holes; (3) **Push fits** (*P*), in which shafts can be pushed into their holes but are not free to rotate without seizing; (4) **Running fits** (*X*, *Y*, *Z*), the most commonly required, in which shafts are of such diameter that they will revolve quite freely and incidentally leave a space for a film of oil. In the Newall table running fits are divided into three grades, viz. *Class X* (the most easy) for engine and other work; *Class Y* for high speeds and good average machine work; and *Class Z* for fine tool work.

In former days, before intensive mass-production was known, it was left to the skill and discretion of the workman to produce and gauge "fits" of various descriptions, just as it was left to his discretion to interpret just what was meant by such dimensions as "⅝ in. bare," or "¾ in. full." Nowadays we have well-accepted systems, devised after long and laborious research, which fix the "high" and "low" (plus and minus) limits of shafts and holes, so securing desired fits as well as interchangeability.

When setting limits on circular holes and their mating parts we often use a set of figures known as the Newall limits. This system has been in use for many years and is universally accepted as sound engineering practice.

Reference to the table on page 11 will show at the top six columns of limits described as "Tolerances in Standard Holes" divided into Classes *A* and *B*. These are the limits which must be given to holes when any of the classes of above fit is required. **It will be seen therefore that the hole dimensions remain constant, while the desired fit is obtained by applying the fit limits to the shaft.**

THE NEWALL STANDARD TABLE OF LIMITS

(FOR SIZES UP TO 5 IN.)

		Nominal Diameters	Up to $\frac{1}{2}$ in.	$\frac{9}{16}$–1 in.	$1\frac{1}{16}$–2 in.	$2\frac{1}{16}$–3 in.	$3\frac{1}{16}$–4 in.	$4\frac{1}{16}$–5 in.
TOLERANCES IN STANDARD HOLES	Class *A*	High limit	+ ·00025	+ ·00050	+ ·00075	+ ·00100	+ ·00100	+ ·00100
		Low limit	− ·00025	− ·00025	− ·00025	− ·00050	− ·00050	− ·00050
		Tolerance	·00050	·00075	·00100	·00150	·00150	·00150
	Class *B*	High limit	+ ·00050	+ ·00075	+ ·00100	+ ·00125	+ ·00150	+ ·00175
		Low limit	− ·00050	− ·00050	− ·00050	− ·00075	− ·00075	− ·00075
		Tolerance	·00100	·00125	·00150	·00200	·00225	·00250
ALLOWANCES FOR VARIOUS FITS	FORCE FITS							
	Class *F*	High limit	+ ·00100	+ ·00200	+ ·00400	+ ·00600	+ ·00800	+ ·01000
		Low limit	+ ·00050	+ ·00150	+ ·00300	+ ·00450	+ ·00600	+ ·00800
		Tolerance	·00050	·00050	·00100	·00150	·00200	·00200
	DRIVING FITS							
	Class *D*	High limit	+ ·00050	+ ·00100	+ ·00150	+ ·00250	+ ·00300	+ ·00350
		Low limit	+ ·00025	+ ·00075	+ ·00100	+ ·00150	+ ·00200	+ ·00250
		Tolerance	·00025	·00025	·00050	·00100	·00100	·00100
	PUSH FITS							
	Class *P*	High limit	− ·00025	− ·00025	− ·00025	− ·0005	− ·0005	− ·0005
		Low limit	− ·00075	− ·00075	− ·00075	− ·0010	− ·0010	− ·0010
		Tolerance	·0005	·0005	·0005	·0005	·0005	·0005
	RUNNING FITS							
	Class *X*	High limit	− ·00100	− ·00125	− ·00175	− ·00200	− ·00250	− ·00300
		Low limit	− ·00200	− ·00275	− ·00350	− ·00425	− ·00500	− ·00575
		Tolerance	·00100	·00150	·00175	·00225	·00250	·00275
	Class *Y*	High limit	− ·00075	− ·00100	− ·00125	− ·00150	− ·00200	− ·00225
		Low limit	− ·00125	− ·00200	− ·00250	− ·00300	− ·00350	− ·00400
		Tolerance	·00050	·00100	·00125	·00150	·00150	·00175
	Class *Z*	High limit	− ·00050	− ·00075	− ·00075	− ·00100	− ·00100	− ·00125
		Low limit	− ·00075	− ·00125	− ·00150	− ·00200	− ·00225	− ·00250
		Tolerance	·00025	·00050	·00075	·00100	·00125	·00125

In this way reamers for holes can be made of standard size, whereas if the fit were obtained by altering the hole and keeping the shaft or mating part constant, it would become necessary to keep great stocks of reamers to cater for the variation in holes due to different fits.

When applying Newall limits to holes, either of the two classes (*A* or *B*) may be used, depending on whether the work is extremely accurate or only moderately so. The reader will note that tolerance is provided for holes which ordinary standard reamers can produce, in two grades, Class *A* and Class *B*, the selection of which is a matter for the user's discretion and dependent upon the quality of the work required. Some prefer to use Class *A* as working limits and Class *B* as inspection limits. We give an example later.

To illustrate the use of the table, suppose we require to dimension a shaft and a hole to obtain a driving fit. Let us assume that the nominal size is 1¾ in. dia., and that a moderately good fit is required. Taking the hole first and applying the Class *B* limits, we see from the table that $\genfrac{}{}{0pt}{}{+\ 0{\cdot}001''}{-\ 0{\cdot}0005''}$ is the limit required.

The dimension for the hole is therefore written 1¾″ dia. $\genfrac{}{}{0pt}{}{+\ 0{\cdot}001}{-\ 0{\cdot}0005}$

The limit for the shaft is obtained by looking along the column *D* to the required diameter. The figure read off will be $\genfrac{}{}{0pt}{}{+\ 0{\cdot}0015''}{+\ 0{\cdot}001''}$

and the full dimension is written 1¾″ dia. $\genfrac{}{}{0pt}{}{+\ 0{\cdot}0015}{+\ 0{\cdot}001}$

Thus we see that limits for circular members are obtained very easily and with certainty to ensure any fit. Apart from this, however, the general question of setting limits to straight work is one which needs great care. It will be realized that the tighter the limits the greater the production costs. With this in mind it should be the aim of any designer to fix his limits as wide as possible, consistent with the successful working of the finished part. While it is true that inspectors do not fix limits, it is well for them to know some of the reasons governing their selection.

Suppose we take Class *A* as working limits and Class *B* as inspection limits. For a $1\frac{3}{4}$ in. dia. hole the limits for the respective plug gauges would be—

$$\text{Class } A\text{: Operator's gauge,}\quad 1\tfrac{3}{4}'' \begin{matrix}+\ 0{\cdot}00075 \\ -\ 0{\cdot}00025\end{matrix} = \begin{matrix}1{\cdot}75075''\ \text{Not Go} \\ 1{\cdot}74975''\ \text{Go}\end{matrix}$$

$$\text{Class } B\text{: Inspector's gauge,}\quad 1\tfrac{3}{4}'' \begin{matrix}+\ 0{\cdot}0010 \\ -\ 0{\cdot}0005\end{matrix} = \begin{matrix}1{\cdot}7510''\ \text{Not Go} \\ 1{\cdot}7495''\ \text{Go}\end{matrix}$$

The advantage of this method lies in the fact that the inspector's gauge does not reject work that the operator's gauge passes. Again, it tends to lengthen the useful life of the operator's gauge. Then, too, the operator's gauge has an advantage over the inspector's gauge in respect of the allowance for wear on the "go" plug, and a similar safety margin on the "not go" plug. Especially in dealing with the coarser tolerances this is the principle frequently followed.

From a **jig and tool** point of view it is convenient to regard limits as being divided into two categories—

1. Limits on the component;
2. Limits that have to be set on the jig or fixture to obtain those on the component.

The first mentioned will always dictate those of the latter; hence it is obvious that if the limits are close on the component they will be as close, or in many cases closer, when it comes to the jig. It may be found occasionally that certain limits on a particular component are so close as to make it practically impossible to obtain them; it then becomes necessary for the jig designer to co-operate with the designer of the component with a view to making alterations forming a compromise. Generally speaking, it is largely carelessness or inexperience that permits limits to be too closely set. When, therefore, the jig and tool designer finds he is in difficulties to cater for certain dimensions, he should never hesitate to take the matter up with the department concerned. Volumes could be written on production difficulties due to limits, and although wonderful achievements in accuracy have been rendered possible, it should not be forgotten that the end must justify the means if the firm is to continue in business.

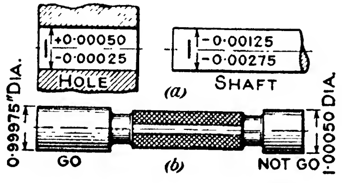


Fig. 2

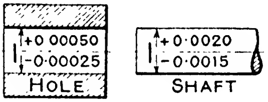


Fig. 3

Broadly speaking, very close limits on jigs are permissible, and for three reasons—

1. They may be necessary on account of the required accuracy of the component.
2. Special equipment for jig and fixture work, such as jig borers, tool-room lathes, millers, etc., is available.
3. The number of jigs required is small, rarely exceeding three or four per job.

Limits should not be set where they are unnecessary, and they should never be more stringent than the requirements justify.

Further Examples. 1. (Fig. 2 (*a*).) Using the Newall table (page 11), dimension shaft and hole, nominal dia. 1 in., running fit, Class *A* limits.

$$\text{Hole dia.} = 1'' \begin{matrix}+\ 0{\cdot}00050 \\ -\ 0{\cdot}00025\end{matrix};\quad \text{tolerance} = 0{\cdot}00075''$$

For a running fit the shaft must be smaller than the hole. A Class *X* fit would give a shaft $\left\{\begin{matrix}-0\cdot00125''\\-0\cdot00275''\end{matrix}\right\}$ less than the nominal hole diameter. Tolerance = 0·0015″.

Thus we have the following dimensions—

Hole: Maximum 1·00050″, minimum 0·99975″
Shaft: „ 0·99875″, „ 0·99725″

Difference between smallest hole and largest shaft = 0·001″.
„ „ largest hole and smallest shaft = 0·00325″.

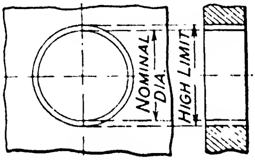
At (*b*) is shown a simple "go and not go" limit plug gauge for the hole.

2. (Fig. 3.) Nominal dia. 1″, force fit. Same hole as in previous example.

$$\text{Dia. of shaft (Class } F) = 1'' \begin{matrix}+\ 0\cdot00200\\+\ 0\cdot00150\end{matrix}$$

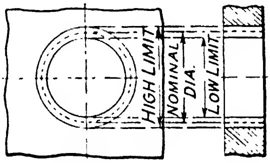
THE B.S.I. SYSTEM OF LIMITS

Having briefly explained the use of the Newall table, let us now examine the British Standards Institution's (B.S.I.'s) system of limits. The British Standard Specification (B.S.S.) applicable to this is No. 164, "Limits and Fits."* At this stage we may continue our explanation of the basic principles of *limiting*, using the B.S.I. terminology. When we speak of a hole of 2 in. dia. we call the 2 in. the *nominal size*. Naturally the actual diameter will not be 2 in. exactly. On a working drawing we shall have to specify limits, and this we can do in one of two ways, viz. **unilateral** (one way) or **bilateral** (two ways).



UNILATERAL HOLE

Fig. 4



BILATERAL HOLE

Fig. 5

Fig. 4 refers to a unilateral hole, the diameter of which may equal the nominal diameter or be slightly larger. Variation is one way only, i.e. only a high limit is prescribed.

In Fig. 5 we show the dimensioning of a hole on the bilateral system in which two-way variation is allowed for, i.e. the hole may be slightly larger or smaller than the nominal diameter, the tolerance extending in both directions (but not always in equal amounts). The drawing (which, of course, is not to scale) shows the largest and smallest possible diameters, respectively called the high and low limits. The difference between these is the tolerance.

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* A new well-illustrated edition was published in 1941.

Summarizing, we may say that in the unilateral system the nominal diameter is the smallest permissible. In the bilateral system the nominal diameter lies between the high and low limits.

The B.S.I. recommend the unilateral system as applied to cylindrical mating surfaces in cases where it does not conflict with predominating present practice. However, in B.S.S. No. 164—1924 provision is made for the use of either unilateral or bilateral limits. A table is also given of graduated shafts suitable for pairing with either the unilateral or bilateral holes.

In this specification we find the importance urged of distinguishing between *mating surfaces*, in which the interrelation between the surfaces in contact is the guiding feature, and *non-mating surfaces*, in which only one surface has to be considered. The recommendation in favour of the unilateral system is confined definitely to *mating* surfaces because for non-mating surfaces either unilateral or bilateral tolerances may be used indifferently, the choice depending mainly upon convenience of manufacture.

The basis of the tables is a hole basis, the limiting dimensions of any hole of a particular quality and size remain unchanged, and varieties of fit are obtained by varying the actual dimensions of the shaft.

Unilateral Holes. Specification by letters is used for various classes of holes. Thus in the unilateral system the letters applicable are *B*, *U*, *V*, *W*. The most accurate are *B*. Class *U* holes are less accurate and are given twice the tolerance of *B* holes. Class *V* holes have twice the tolerance of Class *U* holes, and Class *W* holes have twice the tolerance of Class *V* holes.

In the table given below an example is given, viz. the limits and tolerances of a hole of 2 in. dia. (nominal).

Class of Hole	Low Limit	High Limit	Tolerance
B . .	2·0000 in.	2·0007 in.	0·0007 in.
U . .	2·0000 „	2·0014 „	0·0014 „
V . .	2·0000 „	2·0028 „	0·0028 „
W . .	2·0000 „	2·0056 „	0·0056 „

Bilateral Holes. In the bilateral system the letters used to specify different classes of holes are *K*, *X*, *Y*, *Z*. The most accurate are *K*. The letters *K*, *X*, *Y*, *Z* in the bilateral system correspond respectively to letters *B*, *U*, *V*, *W* in the unilateral. To take an example, a *K* hole of 2 in. dia. nominal has a high limit of 2·0003 in. and a low limit of 1·9996 in. The tolerance (0·0007 in.) is thus the same as that of a *B* hole of 2 in. dia. nominal in the unilateral system.

A study of the B.S.S. (which gives tables of high and low limits for all classes and sizes of holes) will show that the nominal diameter in bilateral holes always falls midway between the high and low limits except where this would result in dimensions of less than half a ten-thousandth of an inch. In these instances the half ten-thousandth is removed from both high and low limits, thus keeping the tolerance the same but bringing the nominal diameter one ten-thousandth of an inch nearer to the upper limit than to the lower limit.

Oversize Holes. The B.S.I. tables also include three classes (*A*, *G*, *H*) of **oversize holes,** each with *two positive limits* of tolerance. The low limit of the hole is larger than the nominal diameter. They are common to both the unilateral and bilateral systems, and are included to meet exceptional conditions. As an example, a Class *A* hole of 2 in. dia. nominal has high and low limits of + 2·8 and + 1·4 (thousandths) respectively.

Range Factors and Size Multipliers. Two tables in B.S.S. No. 164 are of particular value. They are: (1) **Range Factors Table (r),** (2) **Size Multipliers (m).** The usefulness of the range factor tables lies in the fact that it shows at a glance how the tolerance is disposed with respect to the nominal diameter.

In Fig. 6 we show the range factor table. Note how the tolerances are disposed in relation to the nominal diameter. In the extreme left-hand column appears the range factor, reading in ten-thousandths of an inch above, and twenty-thousandths of an inch below, the nominal diameter. It is obvious that the low limit of unilateral holes equals the nominal diameter. The range factor, shown *above* the nominal diameter line, for *B*, *U*, *V*, and *W* holes is 1, 2, 4, and 8 ten-thousandths respectively. In regard to bilateral holes it is clearly obvious that the tolerances are disposed equally on both sides of the nominal diameter line.

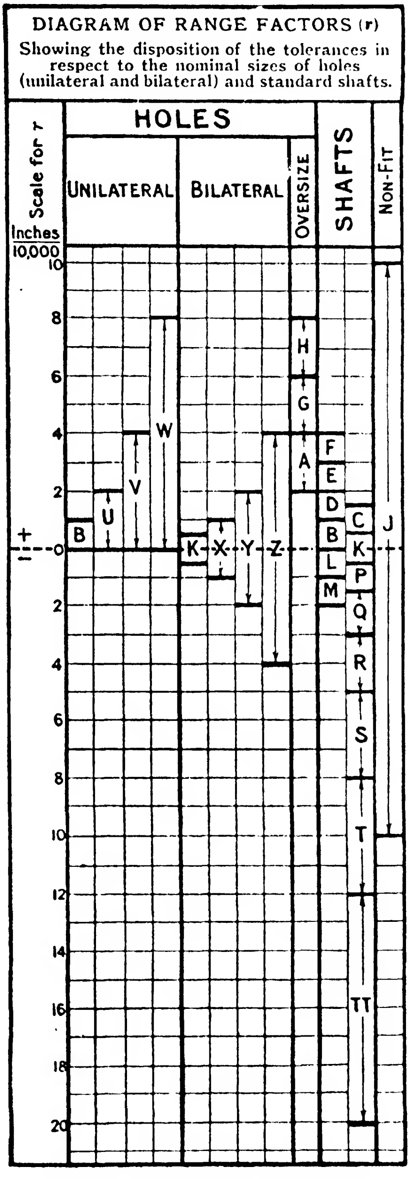
DIAGRAM OF RANGE FACTORS (r)
Showing the disposition of the tolerances in respect to the nominal sizes of holes (unilateral and bilateral) and standard shafts.
Scale for r
Inches 10,000
HOLES
UNILATERAL
BILATERAL
OVERSIZE
SHAFTS
NON-FIT
10
8
6
4
2
+
0
−
2
4
6
8
10
12
14
16
18
20
B
U
V
W
K
X
Y
Z
H
G
A
F
E
D
B
L
M
C
K
P
Q
R
S
T
TT
J

FIG. 6. RANGE FACTOR TABLE

Rule. *To use the table in connexion with some given diameter we must multiply the range factor* (*r*) *by a number which depends upon the particular hole diameter. We call this number the size multiplier* (*m*), *and it is found in the B.S.I. table, a part of which is given in Fig.* 7. *It varies between* 3 *and* 40.

Example 1. For a 2 in. dia. hole the size multiplier is 7. The applicable range factor values for a *B* hole are from 0 to 1. Thus the allowable variation on this hole is from 0 to 7 ten-thousandths of an inch above the nominal diameter. This gives a low limit of 2·0000 in. and a high limit of 2·0007 in.

TABLE OF RANGES AND SIZE MULTIPLIERS (*m*)

Size Multiplier	Nominal Sizes and Ranges
m	inches
3	0 to 0·29
4	0·3 ,, 0·59
5	0·6 ,, 0·99
6	1·0 ,, 1·49
7	1·5 ,, 2·09
8	2·1 ,, 2·79
9	2·8 ,, 3·59
10	3·6 ,, 4·49
11	4·5 ,, 5·49

FIG. 7. PART OF SIZE MULTIPLIER TABLE

Example 2. Hole is 2 in. dia.; *Y*; range factor ± 2; size multiplier 7. The allowable variation is thus 2 × 7 = 14 (ten-thousandths) above and below nominal diameter. This gives a high limit of 2·0014 in. and a low limit of 1·9986 in.

Example 3. Hole is 1 in. dia.; *U*; range factors 0 and 2; size multiplier 6. Thus the low limit is 1 in. + 0 × 6/10 000 = 1 in.; the high limit is 1 + 2 × 6/10 000 = 1·0012 in.

Example 4. Next we can take a *Y* hole of ¼ in. dia. Range factors 2 and − 2; size multiplier 3. The low limit is ¼ − 6/10 000, and the high limit is ¼ + 6/10 000. Limits are 0·2494 in. and 0·2506 in.

Example 5. In the case of a *K* hole we have to deal with odd ten-thousandths of an inch. Take a *K* hole of 2 in. dia. The range factors are ½ and − ½. The size multiplier is 7. Thus the low limit is 2 − ½ × 7/10 000 and the high limit is 2 + ½ × 7/10 000. This equals 2 − 0·00035 in., or 1·99965 in. (low) and 2·00035 in. (high). We next subtract the odd half ten-thousandth from both and finally obtain 1·9996 in. (low limit) and 2·0003 in. (high limit).

Examples to be Worked. Find the upper and lower limits for the following holes: (*a*) *U* hole, 2¼ in. dia.; (*b*) *X* hole, 6¼ in. dia.

(*Answers:* (*a*) 2·2516 in. and 2·2500 in.; (*b*) 6·2512 in. and 6·2488 in.)

Fits of Shafts in Holes. It has already been stated that in the B.S.I. system of limits and fits the hole is the basis of size and fit. The class of hole, unilateral or bilateral, is first chosen, and this enables the diameter of the shaft to be specified in order to give the kind of fit desired. If, for instance, a slack fit is required, it is clear that the shaft diameter must be less than the smallest permissible hole diameter. If a force fit is required, it is equally clear that the shaft diameter must be larger than the largest permissible hole diameter. However, we can no more turn a shaft to any diameter *exactly* than we can bore a hole to an *exact* dimension. Hence we must have a tolerance for the shaft as well as the hole. The extent of the tolerance will depend upon the class of fit desired. In this system there are three main classes of fits, viz. **clearance fits, interference fits,** and **transition fits.** These are defined by the B.S.I. as follows—

(**a**) **Clearance Fit,** where there is a positive allowance between the largest possible shaft and the smallest possible hole.

(**b**) **Interference Fit,** where there is a negative allowance (obstruction) between the largest hole and the smallest shaft, the shaft being larger than the hole. Thus there is an "interference" of metal.

(c) **Transition Fit,** covering cases between (a) and (b), i.e. cases in which the limits admit of either clearance or interference fits being obtained.

In Fig. 8 we show a clearance fit in a unilateral hole.

In the B.S.I. table (shafts) provision is made for fourteen different fits for any particular hole by progressively changing the disposition of the tolerance on the shaft in relation to the nominal size. (See the right-hand columns of the range factor table on page 15.) *The tolerance itself remains unchanged for all shafts in the table from F to M inclusive* (nine shafts lettered *F*, *E*, *D*, *C*, *B*, *K*, *L*, *P*, *M*). All these are of the same standard of workmanship as a Class *B* hole, e.g. in every case for a 1 in. dia. shaft the tolerance is 0·0006 in. The largest shaft is *F* (high limit 1·0024, low limit 1·0018). Running along the table we find that the diameters decrease from *F* to *M*. For shaft *M* we see that the tolerance remains at 0·0006 in., the high limit being 0·9994 and the low limit 0·9988. Shafts *Q*, *R*, *S*, *T*, *TT* become smaller and are given increasing tolerances because they are all considerably undersize and, therefore, provide increasing amounts of clearance when assembled in any hole.

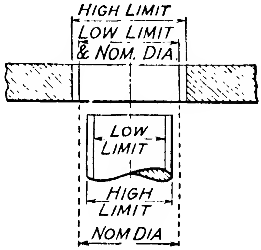

FIG. 8

Example 1. Diameter of shaft 2 in.; Class *F*. (See shaft table (No. 2) in B.S.S. No. 164.) Size multiplier 7; range factors 4 and 3.

This gives a high limit of 2 in. + 4 × 7/10 000 = 2 + 0·0028 in. = 2·0028 in., and a low limit of 2 in. + 3 × 7/10 000 = 2 + 0·0021 in. = 2·0021 in. *This shaft is oversize.*

Example 2. Diameter of shaft 6 in.; Class *B*. Size multiplier 12; range factors 1 and 0. High limit 6·0012 in. Low limit 6·0000 in. *This shaft is oversize.*

Example 3. Diameter of shaft 3 in.; Class *L*. Size multiplier 9; range factors 0 and 1. High limit 3·0000 in.; low limit 2·9991 in. *This shaft is undersize.*

Example 4. Diameter of shaft 3 in.; Class *M*. Size multiplier 9; range factors − 1 and − 2. High limit 2·9991 in.; low limit 2·9982 in. *This shaft is undersize.*

Fits. In B.S.S. No. 164 we find: "*Shafts F to M inclusive are of the same grade of workmanship as a B hole.*"

Suppose that 3 in. dia. class *M* shaft is to be used with a *B* class hole. The high and low limits of the latter are respectively 3·0009 in. and 3·0000 in. (*B* holes being unilateral). Thus a **BM fit,** i.e. an *M* shaft in a *B* hole, would be a **clearance fit,** the largest shaft diameter (2·9991 in.) being smaller than the smallest hole diameter (3·0000 in.). Revise definition of clearance fit on page 16. Sketch a shaft and hole, and compare limiting dimensions. (See Fig. 9.)

The limits for a 3 in. dia. class *F* shaft are 3·0036 in. and 3·0027 in. Thus a **BF fit** would give a minimum **interference** of 0·0018 in. To make this clear, sketch a shaft and hole and compare the limits. Look at the range factor table and note that the high limit of a *B* hole is 1 and the low limit of an *F* shaft is 3. Subtracting 1 from 3 we get 2. Multiplying by 9, the size multiplier, we get 18 (ten-thousandths). This is written 0·0018 in. and is the *minimum interference.* Similarly a **BF fit** for 1 in. dia. would give a minimum interference of 0·0012 in.

Fig. 9 also shows that a **BB fit** is a **transition fit,** for a clearance exists between the high limit of the hole and the low limit of the shaft, while an interference exists between the low limit of the hole and the high limit of the shaft.

Workshop Gauges and Inspection Gauges. The following is taken from B.S.S. No. 164: "The allowance for wear and abuse which is normally made on *workshop gauges* in the interests of economy and life of the gauge reduces the extent of the prescribed tolerances, and this may sometimes result in the rejection of work by the workshop gauges which is within the limits specified.

"*Inspection gauges*, and any measuring instruments used by, or on behalf of, the purchaser should, on the other hand, only reject work which lies outside these limits.

"*Workshop gauges* are used in the course of manufacture to ensure that no work falls outside the limits of fit specified in the table. The tolerances on such gauges fall inside the limits given, and any allowance made for wear must also bring the gauges within the limiting dimensions of the work."

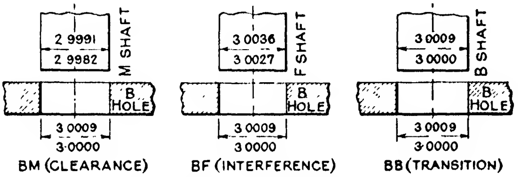

FIG. 9. *BM*, *BF*, and *BB* FITS

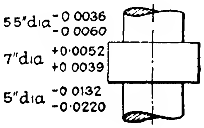

FIG. 10. EXAMPLE OF LIMIT DIMENSIONING

Inspection gauges are used to secure—

(*a*) that the dimensions of the work are such that it can be accepted under a contract;

(*b*) that no work which complies with the specified dimensions is rejected.

Hence the tolerances on inspection gauges are outside the limits of fit specified in the tables, and work may be accepted by such gauges which exceeds the specified limits by amounts comparable with the tolerances on the gauges.

Fig. 10, reproduced from "Recommended Engineering Drawing Practice," published by the Institution of Engineers, Australia, shows a common method of dimensioning at one side of an object. This report also recommends that where limits are shown the nominal size should be given with its limits as shown in Fig. 10.

AMERICAN (A.S.A.) LIMITS

As American textbooks and drawings are used fairly freely in this country it will no doubt prove useful to describe briefly the system recommended by the American Standards Association (A.S.A.) for allowances and tolerances. The following are A.S.A. definitions—

Nominal Size. A designation given to the subdivision of the unit of length having no specified limits of accuracy but indicating a close approximation to a standard size.

Basic Size. The exact theoretical size from which all limiting variations are made.

Allowance (Neutral Zone). An intentional difference in the dimensions of mating parts, or the minimum clearance space which is intended between mating parts. It represents the condition of the tightest permissible fit, or the largest internal member mated with the smallest external member. It is to provide for different classes of fit.

Tolerance. The amount of variation permitted in the size of a part.
Limits. The extreme permissible dimensions of a part.

To show the applicability of these terms suppose a 1 in. shaft to have a free fit (Class 2) in a 1 in. hole. The *nominal size* is 1 in. The *basic size* is the exact theoretical size of the hole, viz. 1·0000 in. The A.S.A. *allowance* for a 1 in. free fit is 0·0014 in. and the *tolerance* 0·0013 in. The limits of the hole would be a minimum of 1·0000 in. and a maximum of 1·0013 in. The limits for the shaft would be the basic size minus the allowance (1·0000 – 0·0014 = 0·9986 in.) as the maximum, and this maximum minus the tolerance (0·9986 – 0·0013 = 0·9973 in.) as the minimum. In Fig. 11 note that the hole dimension has the min. over the max., whereas the shaft has the max. over the min. It is claimed that this adds to convenience in machining.

In Fig. 11 the tightest possible fit (max. shaft in min. hole) would be 0·0014, and the slackest fit (min. shaft in max. hole) would be 0·0040 in.

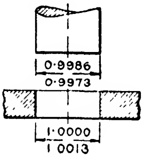

Fig. 11

Classes of Fits (A.S.A.) The A.S.A. tables (*B4a*) classify eight classes of fits with their various limits. When one part is to move in or on another the allowance is positive; when they are to be forced together the allowance is negative, i.e. a shaft would be larger than its hole and there would arise an interference of metal. The fits are as follows—

Loose fit (Class 1): Large allowance.
Free fit (Class 2): Liberal allowance.
Medium fit (Class 3): Medium allowance.
Snug fit (Class 4): Zero allowance.
Wringing fit (Class 5): Zero to negative allowance.
Tight fit (Class 6): Slight negative allowance.
Medium force fit (Class 7): Negative allowance.
Heavy force and shrink fit (Class 8): Considerable negative allowance.

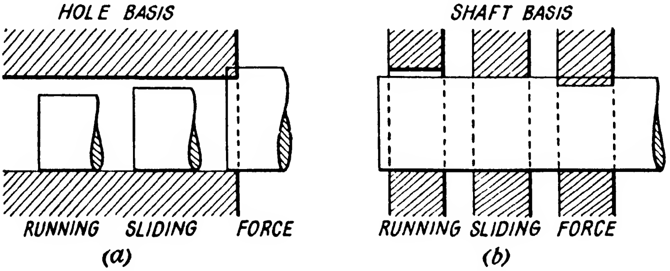

Fig. 11A. Limit Systems, Hole Basis and Shaft Basis

(*a*) The hole is the constant member. Different "fits" are obtained by varying the size of the shaft.
(*b*) The shaft is the constant member. Different "fits" are obtained by varying the size of the hole.

CHAPTER III

METALS LARGELY USED IN MODERN ENGINEERING

It is a truism that of all the metals placed by Nature at man's disposal none has so contributed to his advancement as iron. Indeed it is usual to consider metallurgy as consisting of two great branches, viz. ferrous and non-ferrous. The Latin word for iron is *ferrum* and its chemical symbol Fe.

The products of the iron and steel industry may briefly be summarized as (1) wrought iron, (2) cast iron, (3) malleable cast iron, (4) steel; the basis of all being iron.

CAST IRON. This is reduced in a blast furnace from iron ores. The product is termed *pig iron*, which in addition to an iron content of about 90–95 per cent usually contains about 3–4·5 per cent of carbon (whether the iron be white or grey in fracture) and other metals and substances present as impurities, e.g. silicon, manganese, sulphur, and phosphorus. All these elements have their individual and characteristic effects, not only on the iron but also upon each other. Therefore, given a knowledge of these effects and an ability to limit and utilize them, it would appear that some of the so-called "impurities" may almost come to be regarded as essentials.

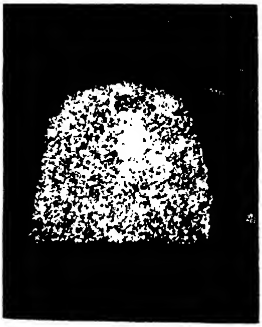

Fig. 12. Pig-iron Fracture

In many works iron from the blast furnace is described as *direct metal* if it is received for a subsequent operation in a molten condition, and *pig iron* if supplied cast in that familiar form; while *cast iron* is the term reserved to describe iron made into castings in the foundry.

Pig iron remelted in a furnace in the presence of hot air loses part of its carbon, and we get cast iron containing about 2·3–3 per cent carbon. Carbon is present in two distinct forms, viz. *combined carbon* (intensely hard and brittle) and *free or uncombined carbon, or graphite* (soft and tough). The proportion of these determines the classification. Various systems of classification are used in different parts of the world, and in different parts of this country, but the following method is the one most generally used and understood. *Fig.* 12 shows a pig-iron fracture (foundry).

Grade No.	Combined Carbon	Graphite	Silicon	Sulphur	Phosphorus	Manganese	Fracture	Brinell Hardness Number
	%	%	%	%	%	%		
1 . .	0·300	3·750	2·60	0·02	Variable	Variable	Open Grey	104
2 . .	0·450	3·500	2·30	0·03			,, ,,	108
3 . .	0·550	3·200	2·00	0·04			Finer ,,	112
4 Forge .	1·000	2·800	1·60	0·10			Fine ,,	160
4 Foundry	0·75	2·100	1·05	0·06			,, ,,	156
Mottled .	2·000	1·600	0·90	0·20			Mottled	350
White .	3·200	Trace	0·65	0·30			White	420

Grey and mottled irons are used for castings, and white for the manufacture of wrought iron and mild steel. Although relatively very brittle and offering poor resistance to shock, cast iron can be cast in a sound condition into intricate shapes which maintain the pattern of the mould. However, the newer autogenous welding methods are now displacing many iron castings in favour of "fabrication" in mild steel. (See pages 132 and 133.)

In aero work one of the main uses for iron is in welding, where it is employed as a filling medium in welded joints. In such work it must comply with the appropriate specification, which calls for a content of 0·1 per cent carbon and for the absence of foaming and spluttering during welding. Another typical use is for aero-engine piston rings.

ANNEALED CASTINGS. Many iron castings are with great advantage given corrective heat treatment, i.e. annealing, in order to reduce internal stresses in the metal and to facilitate machining operations. They are heated to a good red heat and soaked at this temperature. They are then slowly cooled. The effect is to break down the original crystalline formation and substitute a fresh one. Castings so treated suffer a loss of about 40 per cent of their original tensile strength, and are known as *annealed castings* (not to be confused with *malleable castings*).

MALLEABLE CASTINGS. The production of malleable cast iron is achieved by two main methods, viz. (1) the Réaumur process, (2) the Blackheart, or American, process. The starting-point in both processes is good-quality white cast iron low in sulphur and phosphorus.

1. *The Réaumur Process.* After casting to the required shape the resulting white castings, which are very hard and brittle, are packed in airtight iron boxes with iron oxides (e.g. haematite ore), heated for some days in gas ovens, and then allowed to cool slowly. Thus a portion of the carbon in the castings is removed, making them softer and tougher, increasing malleability and ductility as well as tensile strength.

2. *The Blackheart Process.* The practical working of this process is almost identical with the former method, with the important difference that the packing materials used are non-oxidizing, e.g. sand, etc. Temperatures also run somewhat lower. The only purpose of the packing is to prevent the scaling of the castings due to heat. The resulting castings are termed blackheart on account of the appearance of the fracture, which presents a velvety black *heart* or *core*, surrounded by silky grey edges. British white irons are usually too high in sulphur to render them a suitable basis for malleable cast iron.

Malleable castings are softer, tougher, less brittle, and can more easily be magnetized than before. They can be hammered and bent (but not forged) and have an increasing commercial value.

WROUGHT IRON. This is made from cast iron by the puddling process, and is a *fairly pure form of the metal.* It is soft, malleable, and ductile, and its *fibrous* character, induced by the elongation during forging of the slag which it contains, has made it a most useful material for chains, hooks, railway-carriage couplings, etc. Before the introduction of *mild steel*, or "ingot iron," its use was universal for all kinds of forged work, but its uses nowadays are greatly restricted, although some bolts, rivets, etc., are still made from good-quality wrought iron.

Physical Properties. Readily forged and forge-welded. Tensile and ductility tests vary, but the following values are representative: Tensile strength, 23·6 tons/sq. in.; yield point, 15·6 tons/sq. in.; elongation on 8 diameters, 35; reduction of area per cent, 45.

An average percentage composition is: iron 99·31, combined carbon 0·25 silicon 0·12, sulphur 0·13, phosphorus 0·14, impurities 0·05.

STEEL. The difference between wrought iron and steel is that whereas the former is almost pure iron, the latter is a compound of iron with a very small quantity of carbon, varying from 0·1 to 1·5 per cent, and more or less manganese up to about 1 per cent. The great family of steels thus comes intermediate between wrought iron and cast iron in regard to carbon content. In general it may be said that increasing the amount of carbon in steel increases the hardness and tensile strength but reduces the percentage elongation. However, much depends also upon other considerations, e.g. manganese content, and the heat treatment given to the steel. Space does not permit a description of the various manufacturing processes.

It may, however, be mentioned that pig iron can be converted into steel either by taking from it in some way the extra carbon, or by first of all taking out all the carbon and then adding to the iron sufficient carbon to make the required steel. The *Bessemer process* of steel making is based upon the first principle, the *open-hearth or Siemens process* on the second. The best steels are obtained by the second process, as it is not easy in the Bessemer process to eliminate other elements. For certain uses of steel it is usual to specify, in addition to the limits of tensile strength and elongation, that it shall be made by the open-hearth process. By both processes it is possible to produce either *acid* or *basic* steels. From a theoretical standpoint these differ very little, i.e. chemically or physically. The difference lies in the manufacture: phosphorus is removed by the basic process, but not by the acid. As basic steel is cast hotter than acid steel it has a tendency to form *pipes* or shrinkage cavities. Owing to its much less drastic treatment in the furnace and the sounder ingots it produces, acid steel is usually more dependable and uniform in quality than its basic prototype, although with care basic open-hearth steel can be produced in a condition physically indistinguishable from the best open-hearth steel. The latter, however, due probably to its greater density, has a slightly higher tensile strength than basic steel. The *cementation process* consists of converting wrought iron into *blister steel.* If blister steel bars are cut into short lengths, then piled and welded, hammered and rolled, *shear steel* is produced. If the foregoing process is repeated two or three times, *double shear steel* is obtained. By remelting blister steel in fireclay crucibles, *crucible cast steel* is formed. Despite the tremendous development of the Bessemer, Siemens open-hearth and, latterly, high frequency electric crucible process of steel manufacture, the superiority of crucible steel for special purposes—notably high-class tools and cutlery—remains unchallenged.

One preliminary method of classifying steel is according to its carbon content. The early crucible cast-steel makers graded in a system of "tempers" varying by one-eighth per cent of carbon, but in the lower-carbon steels the classification becomes more generalized. The table on page 23 shows these grades and indicates their general usefulness. The high-carbon tempers are taken from a well-known maker's lists.

Thus we have—

1. *Soft, low-carbon,* or *mild steel,* containing from 0·05 to 0·20 per cent carbon. This steel cannot be hardened and tempered by the ordinary methods of heating and quenching, but can be surface- or case-hardened. (See page 50.)
2. *Medium-carbon steel.* This contains from 0·4 to 0·7 per cent carbon. It can be hardened and tempered.
3. *Very hard carbon* or *cast steel* containing from 0·7 to 1·5 per cent carbon. It can be hardened and tempered.

Class or Grade	Carbon	Uses	Remarks
	%		
Mild steel	0·05–0·20	Boiler plate, sheets, tubes, nuts, bolts, rivets, general smiths' work	
Medium-carbon steel	0·40–0·65	Rails, axles, tyres, drop forgings, steel casting	
High-carbon steel—			
No. 6 Temper	0·75	Hammers, general dies, miners' drills, chisels	Easily weldable
No. 5 ,,	0·975	Setts, dies, smiths' tools	Weldable without difficulty
No. 4 ,,	1·00	Hot setts, large punches, large taps, cold chisels, etc.	Weldable with care
No. 3 ,,	1·125	Small taps, punches, reamers, screwing dies	Weldable with great care
No. 2 ,,	1·25	Turning and planing tools, twist drills, small cutters	Not weldable
No. 1 ,,	1·35 to 1·5	Special turning and planing tools	Not weldable

Mild Steel Plate for Aero Work. This should be of the finest quality. It is usually supplied in even numbers of Standard Wire Gauges, e.g. 18 S.W.G., 20 S.W.G., 22 S.W.G. After bending or welding the pieces should be normalized. They should then be straightened or squared up, after which they can be sand-blasted so as to obtain clean descaled surfaces on which flaws can more readily be seen. They may then be cadmium-plated to resist corrosion, after which they may be painted or enamelled.

SPECIAL STEELS. We have seen that what we may call "ordinary steels," or "plain carbon steels," are alloys of iron and carbon containing not more than about 1·5 per cent carbon and more or less manganese up to about 1·0 per cent. The term "special steels" or "alloy steels" is therefore used to describe those steels which owe their wonderful characteristic properties to one or more alloying elements other than carbon, e.g. nickel, chromium, cobalt, molybdenum, vanadium, tungsten, etc.

In our notes on heat treatment we shall see that when carbon steel containing about 0·4 per cent carbon and upwards is heated to a red heat (i.e. 750° C. or above) and quenched in water, the steel will harden. If a hardened steel is reheated and then cooled slowly it can be softened again. Hardening of carbon steels having a carbon content of less than 0·3–0·4 per cent is not a practical proposition.

Alloy steels place at our disposal material having properties and qualities quite unattainable with carbon steel. Sometimes carbon steel may have the necessary mechanical properties, but the use of alloy steels may not entail sacrifice of these and yet save weight. Most readers will be aware that high-tensile alloy steels are used for the highly stressed parts in aero engines.

Some Typical Special Steels

Manganese Steel. Hadfield's manganese steel contains 12–14 per cent manganese and about 1¼ per cent carbon. It was the first alloy steel, i.e. a steel containing an alloying element in considerable proportions, to be applied to practical purposes. Although it contains about 86 per cent of the magnetic metal iron, it is practically non-magnetic. It has a remarkable propensity for hardening up to as high as 600 Brinell hardness under deformation. It has a high resistance to abrasion and is practically unmachinable. When suitably heat-treated it has a tensile strength of 60–73 tons/sq. in.

Nickel-chromium Steels. These are largely used in the aero and automobile industries for such parts as transmission and rear-axle drives, steering knuckles, stressed bolts, connecting rods, etc. The nickel content varies from about 2 to 5 per cent and that of chromium from 0·5 to 2 per cent. It is a typical *high-tenacity steel.* Nickel steels are noted for their high strength, ductility, and toughness, while chromium steels are characterized by their hardness and resistance to wear. The combination of these alloying elements produces steels having all these properties, some intensified.

High-speed Steels. These steels contain from 0·25 to 0·75 per cent carbon, 10–20 per cent tungsten, 2–8 per cent chromium, and sometimes vanadium up to 1 per cent. Like carbon steel, it can be hardened by cooling from a high temperature, and so is suitable for tools for cutting metals. In addition, however, it retains its hardness and cutting powers under the high temperatures—even low red heats—developed in the tool when heavy and rapid cuts are taken, and under which plain carbon steels would become soft and burnt.

An Interesting A.I.D. Classification of Steels. In Inspection Leaflet No. 430 it is stated that apart from a small number of special steels the bulk of the steels used in aircraft and engine construction may be grouped under the following headings—

(*a*) *Carbon steels* (mild, medium, and high-carbon).

(*b*) *Alloy steels* (e.g. nickel 3–4 per cent, chromium 0·5–1·5 per cent).

These may be divided into *medium high-tensile* and high-tensile steels.

(*c*) *Stainless or non-corrodible steels.* These may be divided into the simple or standard 12 per cent chromium, the "two-score," and the austenitic classes of non-corrodible steels.

The Simple or Standard 12 *per cent Non-corrodible Steel.* This contains up to 1 per cent nickel and not less than 12 per cent chromium. It is magnetic, and may be hardened by heat treatment. This class of steel is referred to in D.T.D. Specifications as non-corrodible steel.

Two-score Non-corrodible Steel contains from 1 to 3 per cent nickel and 16–20 per cent chromium. It is magnetic, and may be hardened by heat treatment. This class of steel is referred to in D.T.D. Specifications as high-chromium non-corrodible steel.

Austenitic Non-corrodible Steel (known as "Staybrite" or 18/8) contains not less than 12 per cent chromium and 6 per cent nickel. For practical purposes it is non-magnetic, and can be hardened only by cold working. This class of steel is referred to in D.T.D. Specifications as chromium-nickel non-corrodible steel.

"***Resident and supervising inspectors are responsible for ensuring that all material is in the condition specified in the relevant materials schedules or drawings before it is finally embodied in aircraft or aero engines.***"

FURTHER USEFUL DEFINITIONS

Austenitic Steel. This is usually high in nickel, chromium, or manganese. The usual methods of heat treatment do not greatly vary its physical properties. If quenched from high temperatures it does not harden, and is non-magnetic at ordinary temperatures It has a high resistance to corrosion and erosion by hot gases.

Ternary Steel. Contains iron, carbon, and one alloying element only.

Quaternary Steel. Contains iron, carbon, and two alloying elements.

Complex Steel. Contains iron, carbon, and three or more alloying elements.

Case-hardening Steel. One containing not more than about 0·2 per cent carbon. Two well-known steels of this class with proprietary names are (1) "Ubas," manufactured by Messrs. Flathers. The composition comes within B.S.S. No. 2S.14; (2) "Hicore." This is a nickel-chrome molybdenum steel conforming to B.S.S. No. S.82.

BRASSES. The copper-zinc alloys, with zinc ranging from 0 to 50 per cent, are very important engineering materials on account of their range of mechanical properties, ease of working, and resistance to atmospheric and marine corrosion.

Delta Metal. Copper 55–66 per cent, zinc 38–44 per cent, iron 1·5–4 per cent. This is strong, highly elastic, can be used in rolled or extruded form, and can be cast. A typical "high-tensile brass." (See B.S.S. Nos. 207 and 208.)

Best Brass. Copper 72 per cent, zinc 28 per cent. This is malleable, ductile, rolls well, bright yellow colour.

For Brazing or Silver Soldering. Copper 78–82 per cent; total impurities not more than 1·25 per cent (of which lead must not exceed 1 per cent); zinc, the remainder. Maximum tensile stress is generally specified as not less than 20 tons/sq. in. The tensile test piece has a gauge length of four times the square root of the sectional area of the specimen. A bend test is specified, its nature depending on the size of the specimen.

Brass bars for aero work must be free from surface or other defects such as piping. Bars approved are stamped with the specification number, inspector's identification mark, and the manufacturer's trade mark or symbol.

BRONZES AND GUN-METAL. Copper alloyed with tin forms a series of useful alloys known as bronzes and gun-metal, the former generally being the stronger.

Gun-metal. So called because early guns were made from it. Composition: 85–92 per cent copper, and the rest tin. The more the tin, the harder the gun-metal. It is very tough, finely granular in section, and tenacious. Much used for bearings and for parts subject to corrosive influences. It is readily cast, and is used where stronger castings than in iron are required.

Admiralty Gun-metal. A small quantity of zinc is introduced so as to form an alloy of approximately the following composition: copper 88 per cent, tin 10 per cent, zinc 2 per cent. This is a good bearing metal with a tensile strength of 14 tons/sq. in.

Phosphor-bronze. This is a very strong bronze of the usual copper and tin, but with the addition of a very small quantity of phosphorus, viz. 0·2–1·0 per cent. It has a reddish brown appearance, and can be cast, rolled, or drawn into wire.

Brass and bronze alloys for marine aircraft are protected by one of the following processes: stoving enamel, cellulose enamel, or pigmented oil varnish. The inspection of these is covered by Inspection Leaflet No. 123.

ALUMINIUM. This metal is widely used in general engineering as well as in aero work. During recent times a range of new aluminium alloys has been evolved. Aluminium has certain outstanding characteristic properties, e.g.—

(*a*) *Lightness.* Its specific gravity is 2·68. (For equal volumes its weight is about one-third that of steel.)

(*b*) *Tensile Strength.* Low. Say 6–10 tons/sq. in.

(*c*) *Electrical Conductivity.* About 60 per cent that of copper. Weight for weight, however, it is a better conductor than copper.

(*d*) *Thermal Conductivity.* High.

(*e*) *Resistance to Corrosion.* Good, mainly owing to the natural film of oxide which covers its surface. This film can be thickened artificially by an electrolytic process called *anodic treatment.*

In aero work it is largely used in the form of sheets and tubes. Sheets of not less than 98 per cent pure aluminium (metal up to 99·8 per cent purity can now be obtained) are used in hard, half-hard, and softened conditions. The softened sheets have the lowest tensile strength. Sheets are examined for surface blemishes, e.g. discoloration, blisters, lamination. Mechanical testing is usually limited to tensile and bending tests.

Full information on the inspection of the anodic oxidization process for the protection of aluminium and aluminium alloys used in aero work, including duralumin, is given in Inspection Leaflet No. 8. The anodic treatment may be followed by other corrosion-preventing processes, e.g. stove-enamelling, or by treatment with cellulose enamel or pigmented oil varnish, or by the application of lanoline. (See Inspection Leaflet No. 123.)

Aluminizing and Metallizing. These are spraying processes covered as to preparation of work, spraying, inspection, etc., by D.T.D.s Nos. 907 and 906 respectively.

Aluminium Alloys. The uses of pure aluminium are necessarily restricted by its low-tensile strength, but the addition of small quantities of alloying elements improves mechanical properties, foundry characteristics, etc.

In aero structures the lightness of these alloys enables a much greater volume to be used for a given weight, with a resultant increase in rigidity; high-tensile steels being used for tension members. For high-speed reciprocating engine parts, e.g. pistons and connecting rods, the employment of these alloys leads to better balance, reduced friction, and lower bearing loads. These alloys also allow higher compressions to be employed in internal combustion engines, as when used in the construction of pistons they assist in dissipating the extra heat inevitably associated with high compressions. They have a high coefficient of linear expansion. In a more comprehensive description of these alloys they could be divided into cast and wrought form, and each of these groups could be again divided into those which are hardened by heat treatment and those which are not.

DURALUMIN. In subsequent notes we shall shorten this word to "dural," the name commonly used for it in the shops. It is supplied as forgings, stampings, bars, sheets, tubes, rivets, etc. For exceptional corrosion resistance dural sheets are obtainable with a coating of pure aluminium on each side ("Aldural" and "Alclad"). An average composition of dural is: copper 4 per cent, manganese 0·5 per cent, magnesium 0·05 per cent, iron 0·5 per cent. Its specific gravity is about 2·85. *In the normalized condition* its mechanical properties are—

Ultimate tensile stress	not less than 25 tons/sq. in.
Elongation	15 per cent
0·1 per cent proof stress	not less than 1·5 tons/sq. in.

For workshop processes, e.g. bending, etc., the dural should be softened or annealed by heating it in a salt bath to a temperature of 380° C. ± 10° C., and cooling slowly in air. After working on the metal it should be normalized (temperature 490° C. ± 10° C.), afterwards being cooled off in water. In the heat treatment of dural accurate temperature control is necessary, because when normalizing (or solution annealing) at about 490° C. we are very near to a point at which overheating would cause brittleness. The quenched material is only slightly harder than the slowly cooled alloy, and can be cold worked for simple bends and similar slight working. However, the cold working must be completed within two hours of quenching. For more vigorous working dural should always be annealed. Before being put into service on aircraft dural should be normalized so as to strengthen it and reduce its liability to corrode. After normalizing dural and leaving it to rest at room temperature it is found that hardness increases —rapidly at first, and then more slowly. Cracks may develop if the material is vigorously worked after this "age-hardening." In some cases *artificial ageing* is carried out at 100–150° C. with improvement in yield strength.

The forging and stamping of dural should be carried out at 400–450° C.—never below 400° C., as otherwise cracks may develop.

The control of the heat treatment of duralumin rivets is fully dealt with in Inspection Leaflet No. 426.

DURALUMIN-H. The age-hardening of dural is mainly due to copper and magnesium. Dural-H is a modification of dural containing no copper. Heat treatment consists of water-quenching the alloy from 520° C. followed by artificial ageing at 160–180° C., since there is little tendency for it to age at room temperature.

"RR" ALLOYS. This is a range of casting and wrought alloys developed by Rolls-Royce Ltd. One feature of the series is the controlled use of iron. A second feature is the use of titanium for grain refinement and cleansing.

As an example, RR 56, a forging alloy, has the following mechanical qualities after quenching from 530° C. and tempering at 170° C. for 15–20 hours. Its *B.H. No.* is 140.

Ultimate tensile stress	29 tons/sq. in.
0·1 per cent proof stress	24 ,, ,,
Elongation	15 per cent

Y ALLOYS. This is a cast alloy developed at the National Physical Laboratory. It contains about 4 per cent copper, 2 per cent nickel, 1·5 per cent magnesium, and the rest aluminium.

It can be cast and wrought like duralumin. As in the case of the latter, it requires heat treatment subsequent to working in order to develop its full strength. It undergoes a similar age-hardening process, and attains a final tensile strength in the cast and heat-treated condition up to 22 tons/sq. in.; in the cast state it is about 13 tons/sq. in. Heat treatment consists of heating the castings to a temperature of 500–520° C. for not less than six hours, and quenching in boiling water.

The special characteristic of this alloy is its ability to retain a good strength at relatively high temperatures, a property very desirable in aero-engine pistons.

ALCLAD. Alclad is mainly used for structural work on aircraft. On seaplanes it is used for shell plating of hulls and floats and for stringers, etc. Its outstanding characteristics are light weight, high strength, and good corrosion resistance. The specific gravity is 2·85. It is supplied in sheets consisting of a *core* of light alloy having a coating of aluminium over each surface. The aluminium coating is of high purity and thus offers high resistance to corrosion. Specifications are given in B.S.S. No. L.38 and D.T.D. No. 275.

Alclad is softened by heating to between 360° C. and 400° C. and cooling in air or water. All softened material must be finally heat-treated at 490° C. (plus or minus 10° C.) and quenched in water or oil.

ALPAX. This is an aluminium silicon casting alloy conforming to B.S.S. No. L.33. It has a silicon content of about 12 per cent, and this renders it particularly suitable for intricate and thin-webbed castings, the high silicon content facilitating the flow of the molten metal.

Besides its extensive use in aero work, it is suitable for castings such as are used on compressors, water pumps, petrol engines, carburettors, etc. It is marketed by Lightalloys, Ltd., London.

If *sand cast,* the mechanical properties are—

0·1 per cent proof stress . .	not less than	3·5 tons/sq. in.
Maximum stress	,, ,,	10·5 ,, ,,
Elongation	,, ,,	8 per cent

If *chill cast,* the following are representative results—

0·1 per cent proof stress . .	not less than	4·5 tons/sq. in.
Maximum stress	,, ,,	13·0 ,, ,,
Elongation	,, ,,	8 per cent

HIDUMINIUM. This alloy is also known as "Hiduminium RR 56," and is an aluminium alloy covered by B.S.S. No. L.40. It has a specific gravity up to 2·8 and can be obtained in the form of bars, forgings, and extruded sections. It contains aluminium, copper, nickel, magnesium, iron, titanium, and silicon in proportions set out in the B.S. Specification.

The **heat treatment** of this alloy **for aero work** is as follows. It is carefully heated to a temperature between 510° C. and 535° C. and quenched in water. It is afterwards aged by heating between 155° C. and 175° C. for 10–20 hours. The ageing process may be quickened by heating between 195° C. and 205° C. for a period up to 2 hours. Afterwards it must conform to the following mechanical tests—

Ultimate tensile stress	not less than	27 tons/sq. in.
0·1 per cent proof stress . .	,, ,,	21 ,, ,,
Elongation	,, ,,	10 per cent

"**ELEKTRON.**" This is a magnesium alloy originally of German extraction. The weight of magnesium (specific gravity about 1·75) is only two-thirds that of aluminium, and it can be used (*a*) for saving weight without sacrifice of stiffness, (*b*) for increasing stiffness without exceeding the given weight.

Both wrought and cast magnesium alloys are used. "Elektron" alloy has been substituted successfully for the heavier aluminium alloys in the case of aero-engine pistons, crankcases, etc. Other aircraft uses: control wheels, chain guards, axle blocks. The alloy can be extruded successfully.

D.T.D. Specification No. 59A applies to *castings.*

D.T.D. Specification No. 259 applies to magnesium alloy *bars*, their chemical composition being—

Maximum stress	not less than	17 tons/sq. in.
0·1 per cent proof stress	„ „	10 „ „
Elongation	„ „	10 per cent

(Up to 2 in. dia.)

MONEL METAL. Monel metal varies somewhat in analysis, because it is made directly from an ore containing nickel and copper. It consists of about 68–70 per cent nickel, 26–28 per cent copper, and 3–5 per cent other constituents, e.g. manganese, iron, etc.

For aero purposes it is generally delivered in annealed sheets and bars, but it can be obtained in the form of castings, forgings, wires, nuts, washers, tubes, etc.

For *annealed sheets* the following is a typical specification—

1. *Maximum Stress.* Not less than 30 tons/sq. in. (The 0·1 per cent proof stress is not less than 7 tons/sq. in.)
2. *Close Bend Test.* Test pieces to withstand being bent through 180° (closed down flat) without cracking.

For *annealed bars*—

1. *Maximum Stress.* Not less than 30 tons/sq. in.
2. *Elongation.* Not less than 35 per cent.
3. *Brinell.* Ten per cent of the bars in a parcel are Brinelled. The hardness number is then compared with that of the tensile test specimen. This tests the homogeneity of the material comprising the whole parcel.

Monel metal has been developed for a great variety of uses (it can be forged, stamped, pressed, etc.) by the Mond Nickel Co., whose Bulletins will repay study by inspectors concerned with this metal. Its chief characteristic property is its resistance to corrosion by reducing acids and sea water. A poor resistance, however, is offered to nitric acid, ferric iron solutions, chromic acid, and cyanide solutions. Monel metal can be annealed by heating to 700–950° C., according to the degree of softness required.

K-MONEL METAL. Aluminium added to monel metal forms the material known as "K-Monel." It has the characteristic resistance to corrosion shown by Monel metal, but can be temper-hardened, making it suitable for uses requiring higher hardness and greater strength, besides good resistance to corrosion.

INCONEL. This alloy also shows high resistance to corrosion and heat oxidization, and thus for aero purposes its use is extending. It contains approximately 80 per cent nickel, 13 per cent chromium, and the remainder iron. It is hardened not by heating but by cold working, and by this method its strength can be increased from about 36 tons/sq. in. to about 85 tons/sq. in. To anneal, it is heated to a temperature between 1 000° C. and 1 050° C., soaked for five minutes at this temperature, and allowed to cool in air. Inconel may be soldered, brazed, or welded (oxy-acetylene or metallic arc methods).

CHAPTER IV

MECHANICAL AND OTHER TESTS OF MATERIALS

In the great strides taken by metallurgy during the past thirty years a great additional range of engineering materials has become available. Among these are alloys which, owing to great strength and resistance to fatigue, coupled with lightness, have found uses in aero and automobile work. The development of the aeroplane, in particular, is associated with a great increase in the production of new alloys. Then, too, a range of new tool steels and tool materials has enabled a noteworthy increase in the production capacity of machine tools—indeed in some cases has greatly affected machine-tool design. The use of new materials presents manufacturing problems, especially in forging, machining, and heat treatment, because the manner in which such operations are carried out has an important bearing on the behaviour in service of the manufactured parts.

Mechanical testing of materials is carried out (1) *in investigational work* so as to accumulate data for design purposes and (2) *in acceptance work*, a principal use of which is in verifying that a material is "up to specification." In the latter case the tests should, of course, be simple to carry out, reliable and cheap.

Specification tests, carried out quickly, supply an arbitrary basis for comparison. The determination of some of the constants for the material (e.g. modulus of elasticity), however, requires a lengthy series of skilled operations and is a job best undertaken in an experimental laboratory. After the failure of a part, for instance, it may be necessary to arrange for precise mechanical testing of the material in order to determine whether the failure was due to faulty design or faulty material.

The **B.S.I.** has compiled many specifications recommending tests suitable for a great range of materials. The **Air Ministry** issues *D.T.D. Specifications* of aircraft materials. Lists of the publications of the Air Ministry and the **Aeronautical Research Committee** can be obtained post free from H.M. Stationery Office, Kingsway, London, W.C.2.

The principal mechanical properties of materials are strength, ductility, toughness, hardness, and rigidity. The meanings of these terms should be understood by the present-day inspector. Many specifications relate only to strength and ductility. Naturally, in such short compass, it is only possible to deal briefly with mechanical testing. Inspectors desiring more comprehensive information will find it in Bird's *Engineering Science* books (Pitman) and in Batson's *Mechanical Testing* (Pitman).

Ductility is the ability to withstand a large amount of deformation without fracture, e.g. to "stand up to" permanent extension in a tensile test. Thus a material is ductile if it can be drawn out in tension to a smaller cross-section, as in wire-drawing. Ductility is commonly measured by the elongation and the reduction of the cross-sectional area of a test piece.

Malleability is rather similar to ductility. A malleable material can be permanently deformed without fracture when forged, rolled, hammered, etc.

Toughness is the ability to resist fracture when subjected to a sudden blow, bend, or twist.

Brittleness is lack of ductility, malleability, or toughness.

Hardness is ability to resist denting or scratching by another material. Hard materials resist wear.

STRESS AND STRAIN. When a *force* acts on a body, or a *load* is applied to a member of a structure, a change in dimensions, i.e. *distortion*, is produced in the body. Such distortion may be very small indeed, but highly sensitive testing machines are used to measure it. Distortions thus produced are called **strains.** More accurately **strain is the alteration per unit dimension.** Thus, as a result of a tensile (or pulling) force—

$$\text{Strain} = \frac{\text{Increase in length}}{\text{Original length}}$$

Note that strain expressed in this way is a number or ratio and cannot be given in units of length, weight, force, etc.

When a force acts on a body it not only causes a strain but also sets up a state of affairs *inside the body* known as **stress**. The internal forces which are called into play in the material to resist the tendency of the load to resist strain are called stress. In many cases short bars or test pieces are loaded so as to cause (1) simple lengthening or (2) shortening. Stress and strain come into existence together, and in the case of the former are called **tensile strain** and **tensile stress,** while in the latter they are called **compressive strain** and **compressive stress.** When a piece is distorted by a load which tends to cut or shear it across, we have **shearing strain** and **shearing stress.** For most purposes we assume that the impressed force acts uniformly across the section of the test piece. Then—

$$\text{Stress} = \frac{\text{Load (pounds or tons)}}{\text{Area (square inches)}}$$

Stresses are usually given in pounds or tons per square inch (lb./in.^{2}, or tons/in.^{2}).

MODULUS OF ELASTICITY. In the seventeenth century Robert Hooke established the famous **Hooke's Law,** which forms the basis of many mechanical tests used to-day. He showed that within certain limits the intensity of stress is proportional to strain. Up to a certain load the strains are elastic. In other words, the material returns to its original form and dimensions when the load is removed. The intensity of stress beyond which the material ceases to be elastic is termed **the elastic limit** (E.L.). Beyond this, permanent deformation ensues.

Hooke's law states that within certain limits of loading stress is proportional to strain. The **limit of proportionality** is the intensity of stress beyond which this proportionality ceases to apply. In many materials these two limits, viz. elastic limit and limit of proportionality, are identical. The limit of proportionality (L.P.) is by no means easy to find, and indeed can only be found by most careful tests. It is seldom, therefore, that it is mentioned in commercial specifications, but it is nevertheless most important. Many specimens remain elastic slightly beyond the L.P. until the E.L. is reached. If loaded beyond the E.L. they show slight *permanent set.*

Within the limits of proportionality the ratio of stress to strain is a constant, and we call this ratio the **modulus of elasticity** or simply Young's modulus, after Young, who first made use of it.

Thus in the case of a body subjected to a simple tensile or compressive force—

$$\frac{\text{Intensity of stress}}{\text{Fractional strain}} = \frac{\text{Stress}}{\text{Strain}} = E$$

E being a *constant* or *modulus* depending only on the kind of material. E has also been defined as *that load per unit area which will produce unit strain.*

Consistency of Units. In this work we have to see that units are consistent. Thus the modulus of elasticity is a stress in pounds per square inch only when the stress used is in pounds per square inch and the fractional strain is a true ratio of quantities with like units, e.g. the extension in inches and the original length also in inches.

Example. Calculate the modulus of elasticity of a steel if a bar 10 ft. long, 1½ in. dia., stretches 0·04 in. under a load of 8 tons.

$$\begin{aligned}
\text{Stress} = \frac{\text{Load}}{\text{Area}} &= \frac{8}{0{\cdot}7854 \times (1{\cdot}5)^2} \\
&= 4{\cdot}53 \text{ tons/sq. in.} \\
\text{Strain} = \frac{\text{Extension}}{\text{Original length}} &= \frac{0{\cdot}04}{10 \times 12} \\
&= 0{\cdot}0003333 \\
\text{Modulus of elasticity } (E) &= \frac{\text{Stress}}{\text{Strain}} \\
&= \frac{4{\cdot}53}{0{\cdot}0003333} \\
&= 13\,580 \text{ tons/sq. in.}
\end{aligned}$$

Remember that the modulus of elasticity is a constant for a given material, during the elastic period.

Examples for Self-testing

1. Find the value of E for the material of a wire, 94 in. long and 0·024 in. dia., which stretches 0·083 in. under a load of 12 lb. (*Ans.:* 30 × 10^6 lb./sq. in.)
2. A strut, or column of cast iron, 4 in. dia. and 2 ft. long, carries a load of 22 tons. Calculate (1) the intensity of stress, (2) the amount of compression of the column if E is 8 000 tons/sq. in. (*Ans.:* (1) 1·75 tons/sq. in.; (2) 0·00525 in.)
3. Find the increase in length of a steel bar 6 ft. long and ¾ in. dia. subjected to a tensile load of 4 tons. (*Ans.:* 0·0486 in.)

STRESS/STRAIN OR LOAD/ELONGATION DIAGRAMS. Let us first recapitulate a few important facts. A specimen of mild steel bar loaded in tension with a steadily increasing load will generally behave in the following way. The application of the external load will be resisted by an internal resisting force due to the material itself. During this time the material is in a state of *stress*. At the same time the shape and dimensions of the specimen will alter, and this alteration is called *strain*. As the loading is increased, a period is reached when the internal resisting forces are unable to balance the external load and the material becomes permanently strained. It has then a *permanent set*. It is found that up to the time when permanent set first appears the material is *elastic*, i.e. if the load be removed the specimen resumes its original shape and dimensions. If the material is loaded further (beyond the *elastic limit*) it will *draw out*, gaining length but suffering a decrease in cross-sectional area, until at its weakest point the cross-section will rapidly decrease, forming a *waist* or *stricture*. (See Fig. 13.) Fracture will occur at this waist. We call the load at this time the *ultimate load.*

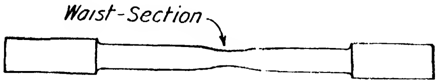

FIG. 13. A TENSILE TEST PIECE

Fig. 14 is a **graph** obtained by plotting tensile stresses and corresponding extensions of a steel test piece. The graph is a straight line up to the L.P. It then slightly curves to the elastic limit (E.L.). Up to L.P., therefore, Hooke's Law applies and strain (extension) is proportional to stress. Up to E.L., on removal of the load, the specimen will return to its original dimensions, thus exhibiting elasticity. Beyond E.L. the graph curves to the **yield point** (Y.P.), demonstrating that extensions are now increasing more rapidly. Just beyond the Y.P. there is more rapid increase in the extensions, but, a little farther along, the curve of the graph indicates that the metal apparently recovers somewhat and extensions do not continue their rapid increase. Farther along still the graph reveals more rapid extensions until the point of **maximum load.** At this point the metal begins to be *waisted* (see Fig. 13) and further extensions occur with very small increments of load until fracture occurs. We have made no mention of *upper yield point* and *lower yield point*, owing to considerations of space.

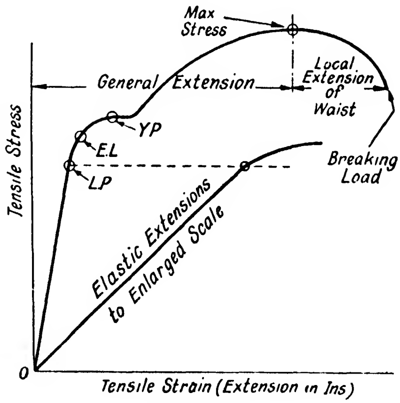

FIG. 14

B.S.I. Definitions. Limit of Proportionality. The L.P. is the point at which the extensions cease to be proportional to the loads. In a stress/strain diagram plotted to a large scale it is the point where the diagram ceases to be a straight line and becomes curved.

[*Note.* It is impossible to determine it in ordinary commercial testing.]

Yield Point. The yield point is the load per square inch at which a distinctly visible increase occurs in the distance between gauge points on the test piece, observed by using dividers; or at which when the load is increased at a moderately fast rate there is a distinct drop of the testing machine lever, or, in hydraulic machines, of the gauge finger.

[*Note.* A steel test piece at the yield point takes rapidly a large increase of extension amounting to more than 1/200 of the gauge length. The point is strongly marked in a stress/strain diagram.]

The **Ultimate Strength** of the material is taken as the maximum load divided by the original cross-sectional area.

This is the value that is required by specifications. Actually, of course, the final stress is considerably higher and is equal to the maximum load divided by the actual cross-sectional area at the point at which the specimen breaks. This value is never used in commercial testing.

For some materials, e.g. the harder steels and non-ferrous metals, there is no sharply defined yielding of the material (or yield point on the graph), and the graph proceeds more or less gracefully from the elastic limit to the maximum load. (See Fig. 15.) For modern aero and similar materials a **proof stress** is inserted in the specification. A defined intensity of stress (specified as the proof stress) is to be applied to the material for 15 sec., and after removal must not have caused a permanent extension of more than (say) 0·5 per cent between the gauge points.

Proof Stress of Aero Materials. The subject of proof stress is comprehensively dealt with in Inspection Leaflet No. 417 (Vol. 2, *Airworthiness Handbook*). Certain B.S. and D.T.D. specifications contain the following requirements in respect of proof-stress determination—

(*a*) For one test sample from each cast, the proof stress shall be ascertained from an accurately determined load/elongation diagram.

(*b*) For all remaining test samples the proof stress shall be ascertained by an approved method.

In Inspection Leaflet No. 417 details are given of the capacity and type of suitable tensile testing machines and grips, of test piece and extensometer type and design.

In regard to the diagram it is recommended that the vertical scale should show *stress* (not *load*). A typical graph and specimen calculations are given in the leaflet, which should be consulted by inspectors interested in these tests.

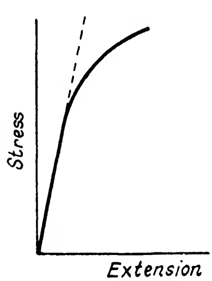

FIG. 15

Two values usually recorded are (1) **percentage extension,** (2) **percentage reduction of area at fracture.**

Let l = original length,
L = final length between the gauge points after specimen has fractured, found by placing the two halves together and measuring,
A = original area,
a = area at point of fracture.

$$\text{Percentage extension} = \frac{L - l}{l} \times 100$$

$$\text{Percentage reduction of area} = \frac{A - a}{A} \times 100$$

A high reduction of area indicates that the material can easily be cold-worked. No. 18/8 stainless steel has a high elongation but a low reduction of area. This indicates that the alloy is tough but hardens very rapidly when deformed.

BARBA'S LAW states that geometrically similar test pieces deform similarly when tested in tension. Two test pieces are geometrically similar when the ratio between their respective gauge lengths is the same as the ratio between their respective transverse dimensions. With cylindrical pieces of the same material but different diameters, the percentage extension is constant if the ratio of the gauge length to the square root of the cross-sectional area is constant—

$$\frac{\text{Gauge length}}{\sqrt{(\text{Cross-sectional area})}} = \text{Constant}$$

It is unfortunate that the same constant is not used in different countries. In British practice it is $4\sqrt{(\text{area})}$, which is 2 in. for a diameter of 0·564 in.

General and Local Extension. We have seen that when a test piece is gradually loaded it extends all along its length until the maximum load is reached, and this is called the *general extension*. Afterwards, until fracture, the extension or "drawing out" takes place at the waist, and this is called *local extension*.

General extension + Local extension = Total extension

In Fig. 16 we give a line diagram of a carbon-steel test piece before and after fracture by tension. The elongation in this test was 22·5 per cent on a gauge length of 2 in., tenacity being 44 tons/sq. in.

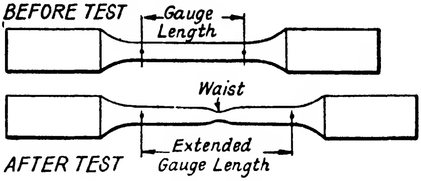

FIG. 16. TENSILE TEST PIECE

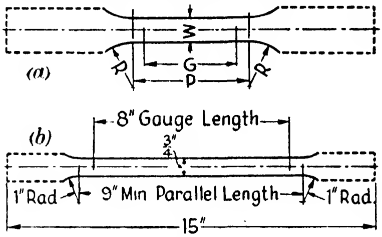

FIG. 17. B.S. FLAT TEST PIECES

Fig. 17. These are the B.S. test pieces for sheets, plates, flat bars, sections, etc. Test piece *A* has a width *W* of ½ in., 1 in., or 1½ in. for plates less than ⅜ in. thick. For plates of ⅜ in. thick and over, *W* = 1½ in. (max.). Test piece *A*–1 is for special strip and sheet materials.

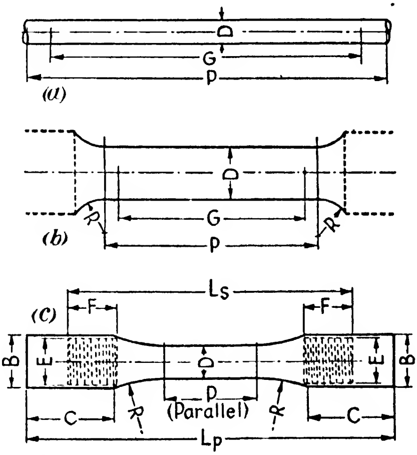

FIG. 18. B.S. ROUND TEST PIECES

Fig. 18. At (*a*) is shown test piece *B* for unmachined bars, etc., up to 1 in. dia. Gauge length $G = 8D$.

At (*b*) is shown test piece *C*. It is machined to size. Gauge length $G = 2$ in. Diameter $D = 0·564$ in. Area in cross-section = 0·25 sq. in.

At (*c*) is shown tensile test piece for cast iron.

For dimensions and full description, see B.S. 18—1938(modified 1940).

TYPICAL TESTING MACHINES

1. **10-Ton Vertical Single-lever Testing Machine** (Buckton-Wicksteed Patent) (Fig. 19). This is a reliable machine made by Joshua Buckton & Co. Ltd. It imposes and measures loads up to 10 tons, and takes specimens in tension up to a maximum stretched length of 20 in. between the grip boxes. It may be remarked that the *single-lever* vertical type of machine has been used extensively in this country, but on account of its smaller floor space the *compound-lever* machine, previously made almost exclusively in America, is now manufactured in this country by W. & T. Avery & Co. Ltd. and Joshua Buckton & Co. Ltd.

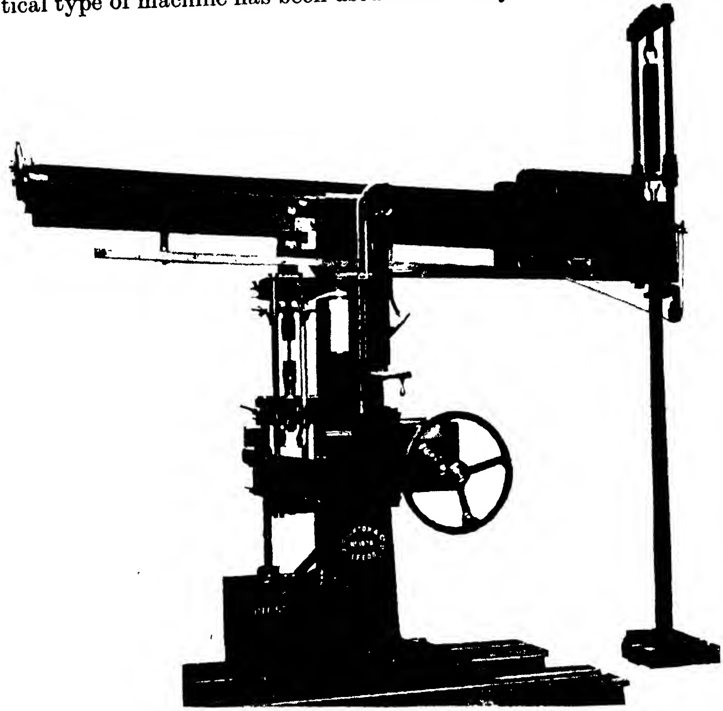

FIG. 19. A 10-TON VERTICAL SINGLE-LEVER TESTING MACHINE
(*Buckton-Wicksteed Patent*)

Essentially a testing machine consists of *a straining unit* and *a weighing unit*. The straining unit *does the work* on the specimen and is either hydraulic or mechanical; the weighing unit *measures the work* applied and may be of single- or double-lever type, either type working with a *poise weight* in one, two, or three parts. The poise weight is propelled along the steelyard by means of toothed gears and a long screw thread, the latter passing through a tapped hole in the poise weight. The propelling gear may be hand-, belt-, or motor-driven.

The poise in weight in Fig. 19 is 10 cwt. and is moved along the equilibrated lever by hand. A scale and vernier are carried from the lever and graduated to read in tons, tenths, hundredths, and thousandths of a ton. The machine is fitted with the *Buckton-Wicksteed patent bridle,* which prevents deleterious effects due to shock when a test piece breaks and increases the endurance of the knife-edges.

The *straining head* is driven by a 2 h.p. series-wound electric motor, with hand gear in addition for use when very slow testing speed is required, through tangent gearing actuating two direct screws and nuts. The machine is fitted with a *pointer* for indicating the movement of the steelyard, and for showing when it is level. The *grip boxes* for holding the test pieces are of a lever-operated type, the grips being set or released by a simple motion of one lever on each grip box.

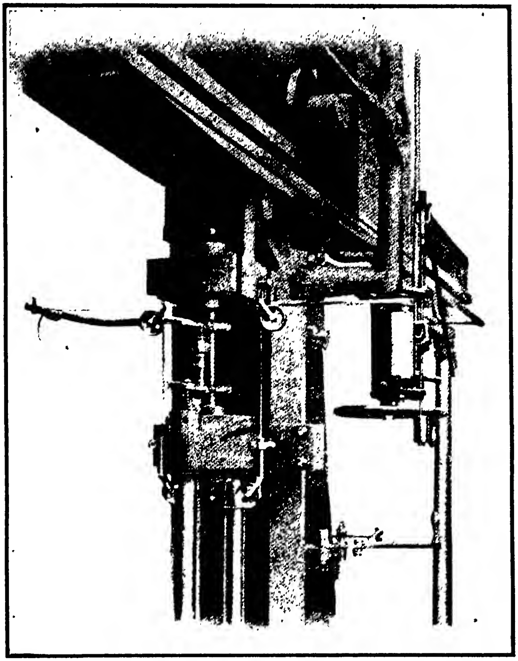

FIG. 20. BUCKTON-WICKSTEED AUTOGRAPHIC RECORDER

The Buckton-Wicksteed Patent Spring-balanced Autographic Recorder (Fig. 20) is shown attached to a single-lever testing machine. It furnishes a graphic record of the behaviour of the specimen under test.

When the *recorder* is in use the poise weight is retained in a fixed position on the beam, the outer end of which is suspended by a spiral spring whose characteristics are known. Thus the load on the spring is relieved by the amount of the actual load taken by the specimen, and the small movements of the end of the beam give a direct measure of the load carried by the specimen. The barrel of the recorder, which carries a sheet of squared paper, is rotated by a tape connected by pulleys with the two cross-heads of the testing machine, in such a manner that the extension of the specimen produces an exactly corresponding rotation of the barrel. The pencil carriage is connected by another tape to the end of the beam, and thus the movements of the beam are communicated to the pencil. In the result, a diagram showing the exact extension and load on the specimen at every moment of the test is drawn upon the paper, and the diagram gives an unmistakable record of the elastic limit, the yield point, and the percentage extension.

2. **100-ton Horizontal Multi-lever Testing Machine** (Fig. 21). This machine is made by W. & T. Avery Ltd., and the block is taken by permission from Pitman's *Engineering Educator*. In the diagram is shown the weigh lever *L* connected to the grips *G* through two links *P* and *M*, and a bell-crank lever *B*. A Hele Shaw pump *H* operates the hydraulic straining gear.

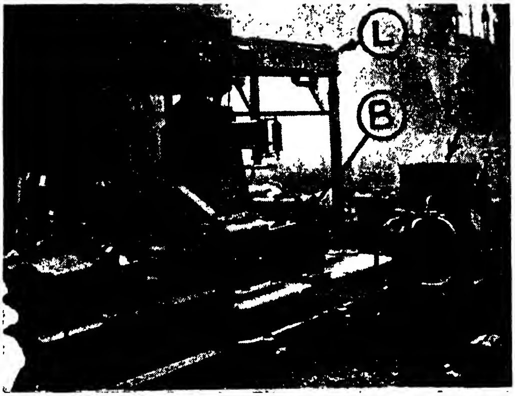

Fig. 21. A 100-ton Horizontal Multi-lever Testing Machine

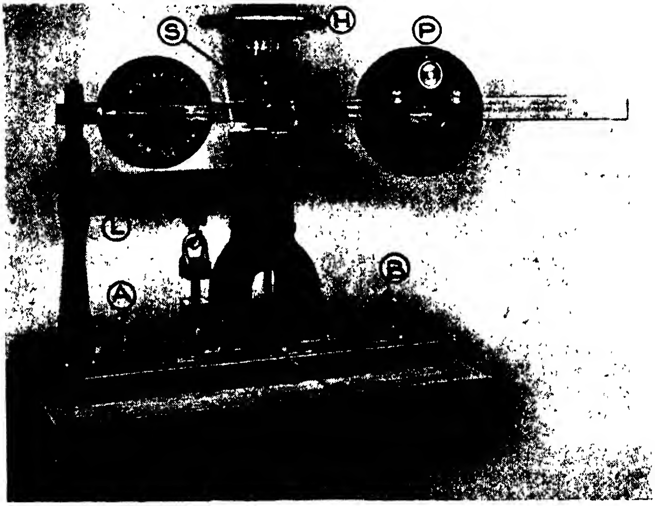

Fig. 22. Avery Testing Machine for Cast-iron Beams

3. **Testing Machine for Cast-iron Beams** (Fig. 22). This machine is made by W. & T. Avery Ltd., principally for bending tests on cast iron. For cast iron the British Standard test for specification purposes is a bending test on a rectangular bar 1 in. wide, 2 in. deep, and 40 in. long tested on a span of 36 in. with a central load as shown in Fig. 23. The strength is measured by the central load at fracture; the deflection at the centre of fracture is also usually specified.

Of course, bending tests can be carried out in the *universal* testing machines in common use, but in foundries and test houses where many cast-iron beams have to be broken daily special machines, of which Fig. 22 may be taken as an example, are installed.

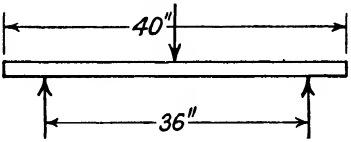

FIG. 23. B.S. TEST PIECE

The beam is supported at *A* and *B*, and the central load is applied at *C* by a rod attached to one knife-edge of the weigh beam. Along the latter the counterpoise *P* is moved by a small handle and gearing *S* to apply the load. The beam is kept floating by the handwheel *H*, to which a scale is attached for measuring the deflection. A special arrangement *L* is attached to this particular machine for carrying out tensile tests on cast iron.

NOTCHED-BAR TESTING. Differences due to mechanical and heat treatment not indicated by tensile tests are disclosed by the notched-bar tests, which many authorities consider a reliable measure of toughness. This method was developed by Izod and others in comparatively recent times, and the tests now to be described are often called Izod tests. During the war of 1914–18 Izod tests were largely applied to aero materials, and nowadays such testing is extensively undertaken. Two methods of carrying out the test have been standardized by the B.S.I.

Method 1 (see Fig. 24). A notched test piece, 10 mm. square by 60 mm. long, is arranged on supports 40 mm. apart and is struck at the centre (opposite the notch) by the tup of a hammer. The energy absorbed from the hammer in breaking the test piece is measured. Cylindrical notched test pieces are also used and are approved by the Air Ministry.

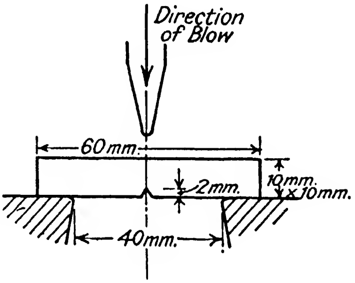

FIG. 24. NOTCHED TEST PIECE

Method 2 (see Figs. 25 and 26). A notched test piece, either 10 mm. square section or 0·45 in dia. is gripped as a cantilever in a vice, with the root of the notch level with the top of the vice, and broken by a blow applied 22 mm. above the top of the vice. The vee-notch has an angle of 45° and a filleted root. (See Fig. 25.)

The machine generally used for these tests consists of a weighted pendulum swinging on ball bearings and having its centre of percussion at the point at which the test piece is struck. The pendulum is raised to a standard height and allowed to strike the "notch side" of the specimen.

The striking energy of 120 ft./lb. is partially absorbed in fracturing the specimen, and this amount is indicated by the pointer. The main effect of the notch design is that stresses are set up at its root which are higher than the average value, indeed the sharpness of the notch largely controls the test.

Some modern opinions now consider that the Izod test does not very usefully measure the resistance of the material to impact, since the velocity of the testing is so low.

Main Purposes Served by the Izod Tests

1. It is generally understood that the main purpose is to indicate *toughness*, or resistance to shock.

2. It measures the resistance of a material to *the spread of a crack* after it has once formed. Materials with low Izod figures offer low resistance to the extension of cracks. Thus a low Izod value indicates that in service such materials offer great chances of final fracture before such cracks are discovered.

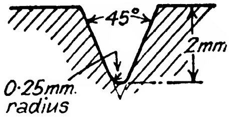

FIG. 25. NOTCH DIMENSIONS

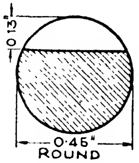

FIG. 26. SECTION OF CYLINDRICAL NOTCHED BAR

3. In the case of brittle metals it gives a guide to their resistance to fracture at a *discontinuity*. In other words, it gives a guide to their capacity for resisting the effects of *stress concentration* at a *change of section*. Then, too, useful information is gleaned from an inspection of the fracture. For example, in the case of mild steel, though the *general fracture* may show crystal facets, the width of the dark area beneath the notch indicates the resistance to the early spread of the crack. Again, experts find that an inspection of the fracture yields guidance as to suitable tempering temperatures for alloy steels, or even absence of correct heat treatment.

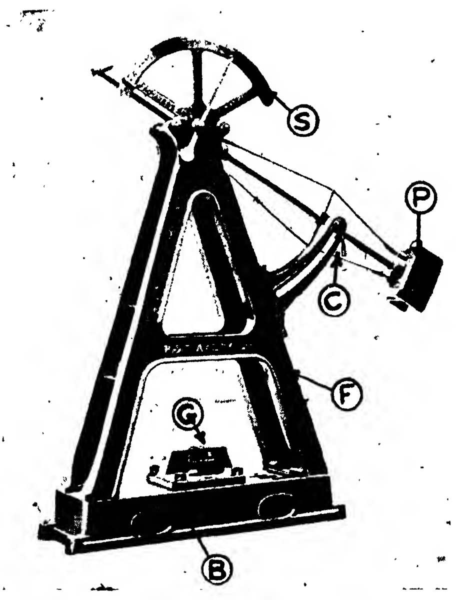

FIG. 27. IZOD IMPACT-TESTING MACHINE

(By courtesy of W. & T. Avery, Ltd.)

The Testing Machine (Fig. 27). This is an Avery machine (notched-bar testing machine, cantilever (Izod) method). The base *B* supports two cast standards *F*. At the top of this is the axis of the pendulum *P*. An extension of the pendulum works a pointer which moves over a scale *S*, which is graduated to read in ft./lb. The catch *C* releases the pendulum.

X-RAY EXAMINATIONS. The use of aluminium and other light-alloy forgings and castings for the stressed parts of aircraft has caused means to be devised for detecting flaws in such parts without damaging them. Especially is this necessary when proof loading is impossible. X-ray examinations are the only conclusive and practical non-destructive, non-weakening, and non-disfiguring tests which may be made on the finished article. Tests of a mechanical or other nature usually have to be carried out either upon samples of the raw material or, at best destructively, upon representative specimens.

Inspectors specially interested in Radiology are referred to *Metallurgical and Industrial Radiology* by K. S. Low (Pitman), from which Fig. 28 is reproduced by arrangement.

X-rays travel in straight lines and can penetrate matter which is opaque to light. The resistance of a substance to penetration is roughly proportional to its density. Lead is therefore opaque relative to aluminium for a given radiation. "Hard" rays (with short wavelengths) are more penetrating than "soft" rays (with longer wavelengths).

The depth and extent of defects, e.g. blowholes, cracks, etc., in castings, forgings, and welded parts are revealed on the films because such defects offer less resistance to the rays than is offered by sound metal. Thus their presence is indicated by dark areas on the film or light areas on the positive print.

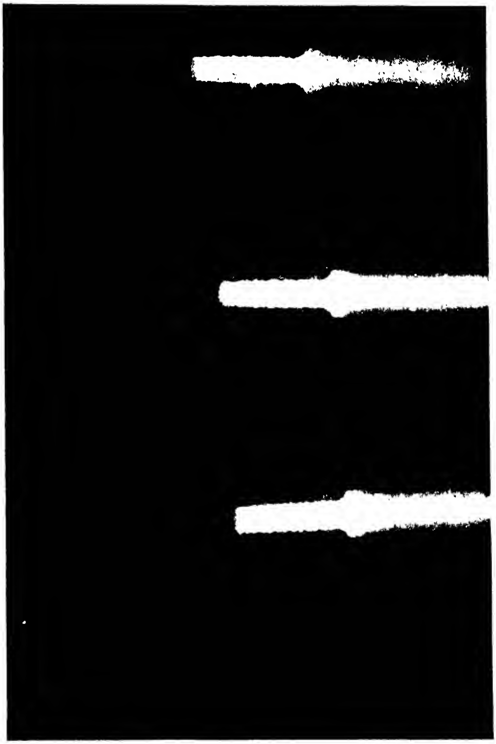

FIG. 28. MAGNESIUM-RICH ALLOY CASTING CONTAINING A STEEL INSERTION

Showing a large void at the junction which is nevertheless entirely enveloped by a thin surface of the alloy, so that there is no external indication of the trouble.

X-ray inspection of welds reveals internal defects, e.g. cracks, porosity, etc. Welded drums and pressure vessels for steam plant are finally inspected in this way.

Gamma-ray Examinations. The gamma-ray method is more recent, but is similar to X-ray inspection. The gamma rays emanate from radioactive substances, e.g. radium or a gas from radium. The ray penetrates the metal more quickly than the X-rays and is used for inspecting heavy work which would require very long X-ray exposures.

Magnetic Dust Method. The steel article is first magnetized and then immersed in a bath of kerosene which contains fine iron dust. Supposing a crack lies across the path of the magnetic flux, then each side of the crack becomes a magnetic pole which serves to collect iron dust. Surface flaws and cracks are thus indicated by the presence of dust. This "magnaflux" test is useful in tool-rooms.

WOODS. Engineering uses are—

Ash and *Beech*: Hammer shafts and tool handles.
Ash and *Spruce*: Aircraft work.
Walnut and *Mahogany*: Wooden airscrews.
Beech and *Hornbeam*: Mortise wheel teeth ("cogs").
Yellow Pine: Patterns.
Mahogany: Patterns (small).
Maple: Wood pulleys.
Box: Mallets, sheaves of pulley blocks, bearings.
Lignum Vitae: Machine-tool handles, bearings under water, etc. Has a high specific gravity and is hard and heavy.

INSPECTION OF TIMBER. The Air Ministry require that before any timber is issued to the shop for the manufacture of aircraft main structural members, e.g. spars, flanges, and webs of built-up spars, longerons, and struts (undercarriage, interplane, fuselage, and wing compression), it must be tested for—

(1) freedom from brittleness,
(2) the correct moisture content,
(3) the specified density.

Subsidiary timber parts need not be subjected to these tests, but *must* be *visually examined* for quality and freedom from deleterious effects *on completion of manufacture*. Where both grades of timber are used simultaneously in a shop it is essential to provide adequate, i.e. "foolproof," means of indentification.

Determination of Brittleness

Method A. A plain test piece cut parallel with the grain, 12 in. long by 1 in. square, or to the size given in the specification, shall be prepared with the sides cut radially and tangentially, and the blow shall be applied in the tangential direction.

The testing machine shall consist essentially of a freely falling, vertically guided weight of 24 lb., the striking surface of which shall be cylindrical, with a radius of 3 in. The weight shall be dropped (through distances 4 in. to 8 in., depending on the kind of wood) on to the test piece when the latter is placed centrally on supports 10 in. apart. These supports shall have a $\frac{1}{4}$ in. radius on the inside upper edges. See Fig. 29 for a typical machine. The opening-out of a few fibres on the under or tension side shall not be taken as indicative of failure.

Method B. A notched test piece, the sides of which are cut radially and tangentially, of the dimensions shown in Fig. 30, shall be broken in an impact testing machine of the type shown in Figs. 31 and 32, the blow being applied in the tangential direction.

The Air Ministry's requirements are (1) a test piece shall absorb not less than 6 ft. lb.; (2) a tolerance of — 0·5 ft. lb. may be allowed at the discretion of the inspector, provided the fractured specimen shows a satisfactory amount of fibre.

Determination of Moisture Content. The inspector shall indicate the position from which a small sample of timber shall be cut. A specimen about $\frac{1}{4}$ in. thick, cut transversely to the grain, can be weighed on an approved chemical balance. Let its weight be W_1. The sample shall then be dried in a suitable oven maintained at a

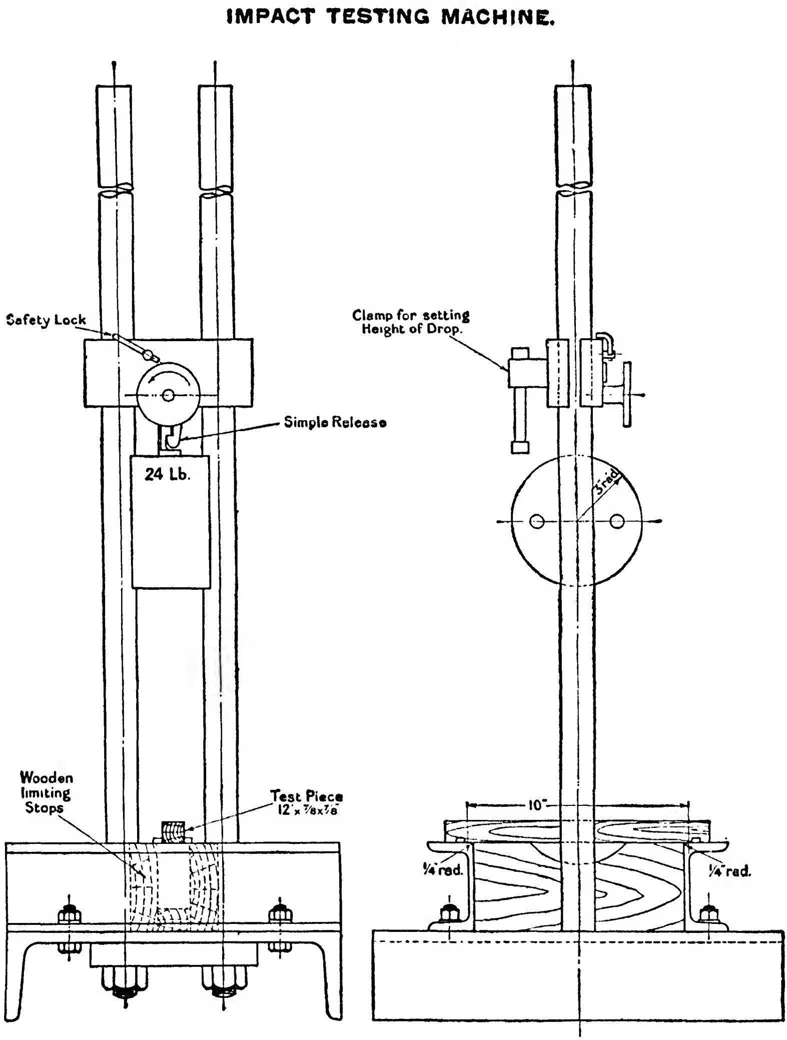

Fig. 29. Views of a Simple Drop Impact Testing Machine
(By courtesy of The British Standards Institution)

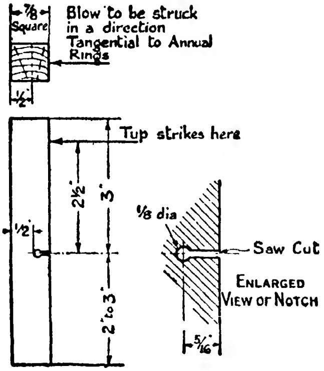

FIG. 30. STANDARD TEST PIECE

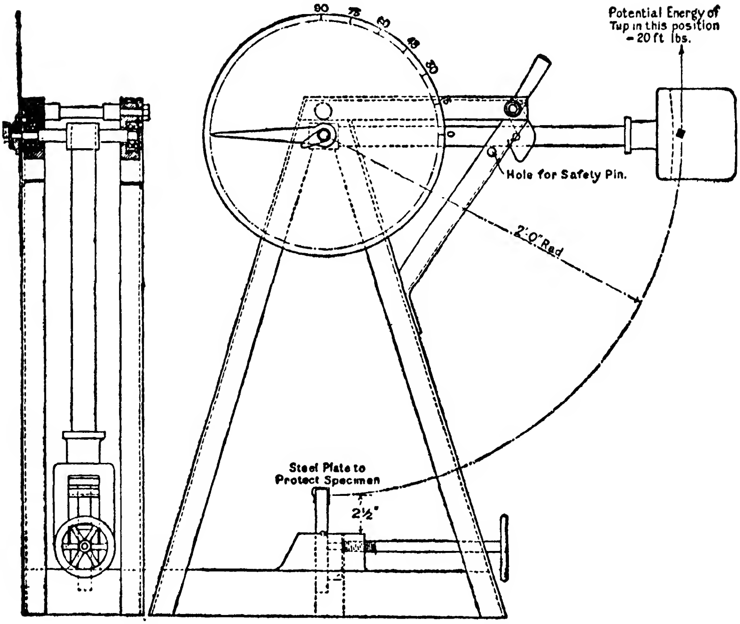
90
75
60
45
30
0
Potential Energy of Tup in this position = 20 ft lbs.
Hole for Safety Pin.
2'0" Rad
Steel Plate to Protect Specimen
2½"

FIG. 31. VIEWS OF IMPACT-TESTING MACHINE

(By courtesy of the British Standards Institution)

temperature of 221° F., until two successive weighings are identical. Let W_0 be weight after desiccation. Then—

$$\text{Percentage of moisture} = (W_1 - W_0)/W_0 \times 100$$

Great care should be taken to prevent any change in moisture content between the cutting of the sample and the first weighing, or between the removal from the oven and the subsequent weighing.

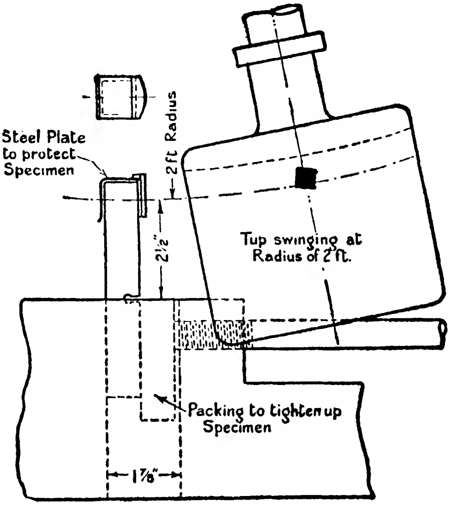
Steel Plate to protect Specimen
2 ft Radius
2½"
Tup swinging at Radius of 2 ft.
Packing to tighten up Specimen
1⅞"

FIG. 32. ENLARGED VIEW, SHOWING TEST PIECE IN POSITION IN TESTING MACHINE

(By courtesy of the British Standards Institution)

Determination of Density. The density shall be determined by weighing and measuring the volume of a sample from the plank. The determined density shall not be less than that stated in the table in Inspection Leaflet No. 7. See *Airworthiness Handbook* A.P. 1208 at the equivalent moisture content.

Determination of End Grain Compression Strength. Three test pieces shall be turned from each sample to be tested. The test pieces shall be turned to the dimensions given in Fig. 33. The ends should be smoothed off with a chisel to remove the centre pip usually left after turning. As an alternative the test pieces may be cut 1 in. square and 2 in. long. Loading *must* be applied evenly and not too rapidly, otherwise the results will be respectively lower or higher than the true value. At the end of about a minute special observation of the behaviour of the beam of the testing machine must be made because maximum loading will occur.

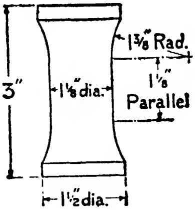

FIG. 33. END-GRAIN COMPRESSION TEST PIECE (B.S.I.)

One recommendation is that loading should be arranged so that the rate of increase in stress in the test piece may be 3 000–6 000 lb./sq.in./min. For any one timber three tests should be made, both for ultimate compressive stress and for moisture content.

Determination of Young's Modulus of Elasticity and the Modulus of Rupture

The Test Piece. The size of the test piece shall be 40 in. long and shall have a rectangular section 2 in. deep by 1 in. wide, or preferably a square section 2 in. by 2 in. It shall be cut with the length parallel with the grain and preferably with the depth parallel with the radial face of the test piece, the heart side being uppermost.

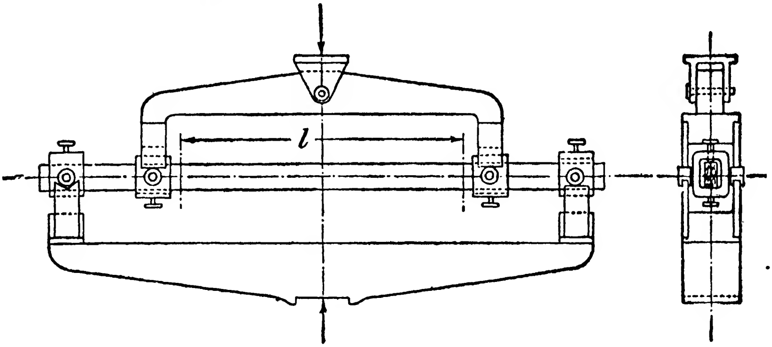

Fig. 34. Beam Test Machine
(*By courtesy of the British Standards Institution*)

The Beam Test. Four-point loading is preferred for the beam test so as to avoid additional deflection due to lateral shear in the middle part of the beam where deflection is measured. The application of the load should be in the neutral plane of the beam in such a manner as to prevent longitudinal loading of the beam as well as local crushing. (See Fig. 34 for a suitable beam test machine.) A series of deflections corresponding to increasing loads should be measured on the beam between the central loading points. When plotted as a graph the results should fall on a straight line up to the elastic limit.

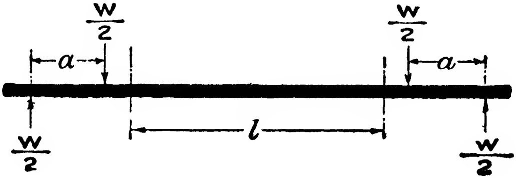

Fig. 35. Beam Test Diagram
(*By courtesy of the British Standards Institution*)

If W_1, W_2, and d_1, d_2 are the loads and corresponding deflections for any two points on this straight line, the value of E is given by—

$$E = \frac{3\,(W_1 - W_2)}{4\,(d_1 - d_2)} \cdot \frac{al^2}{bh^3}$$

where a = distance between the outer point of support and the adjacent inner loading point (see Fig. 35),

l = length (of the neutral axis) at the centre of which deflection has been measured,
b = breadth of beam,
h = depth of beam.

(All dimensions being in inches.)

The modulus of rupture is calculated from—

$$\text{Modulus of rupture} = 3Wa/bh^2$$

where W is the load required to break the test piece.

The method just described is called "four-point loading" and is standardized by the B.S.I. Tests on timber are carried out in America by means of central loading, and an endeavour is being made to introduce the same method in this country.

INSPECTION OF PLYWOOD. Plywood is largely used in airframe work, and the detailed process inspection of plywood for use in structurally important parts, e.g. fuselage sides, spar construction, etc., as well as for use in subsidiary parts, e.g. fairings, etc., made of this material is provided for comprehensively in Inspection Leaflet No. 41, which is contained in the *Airworthiness Handbook*, Vol. 2 (Inspection section). Separate instructions are given in respect of (1) British-made plywood and (2) imported plywood.

The plywood used generally consists of three veneers of wood glued or cemented together under pressure. The grain of the outer plies runs longitudinally with the length of the board, whereas the grain of the middle ply runs at right angles to that of the outer plies. "Multi-ply" is the name given when more than three plies are used. Among the materials used for the outer faces of three-ply are birch, mahogany, and teak. As the middle ply of "hard-core" material, birch is commonly used; while bass, mahogany, and poplar may form the centres of "soft-core" material. In this manner very strong plywoods are produced.

The mechanical testing of representative samples of plywood is undertaken at *approved test houses* to check compliance with specification requirements. Inspectors concerned with plywood should study Inspection Leaflet No. 41, B.S.S. No. 4V.3, and other relevant sources of guidance.

Inspection of Glued Parts. See Inspection Leaflet No. 435. The gluing of structurally important parts must be done under approved conditions, and the inspector is responsible for seeing that these conditions are maintained. The inspection of a glued component being limited to a visual examination, the inspector must necessarily rely to a considerable extent upon his knowledge of the efficiency with which the gluing has been done. Detailed guidance is given in the leaflet on materials and methods.

CHAPTER V

HEAT TREATMENT AND HARDNESS TESTING

In modern engineering practice very little steel is used in its "raw state." Steel, for whatever purpose it may be required, benefits by some form of heat treatment, chosen to improve its physical properties and render it most suitable for the job or the operation in view. Heat treatment may be divided into three main headings, viz.: (1) hardening and tempering, (2) annealing and normalizing, (3) case-hardening.

HARDENING consists of heating the steel to a temperature beyond its upper critical range and cooling it rapidly in water, oil, or air.

When referring to **critical points** (or "*A*" points) in carbon tool steel we mean the temperatures at which certain changes take place both in microstructure and physical properties during heating and cooling. Any change in constitution or rearrangement of the atoms constitutes a critical point. For instance, the upper critical point has been defined as the temperature at which a steel, on cooling naturally, commences to precipitate the carbon previously in solid solution in the form of cementite. The iron, previously in "gamma" form, becomes known as "alpha" iron.

When the steel is heated to a certain point (the **decalescence** point), it continues to absorb heat but its temperature remains practically the same. In the same way, if steel is cooled from a high temperature it will, at the **recalescence** point, actually increase in temperature. The recalescence point is lower by 85° to 215° F. than the decalescence point. In the hardening process these critical points are of great significance. If the steel is not uniformly heated up to, or slightly beyond, its decalescence point and then suddenly cooled *before* it reaches recalescence point, it cannot be hardened. Steel heated beyond its decalescence point is non-magnetic. This fact is the basis of certain methods used to *discover* the decalescence point.

At normal temperatures steel has its carbon (the chief hardening element) in a form known as **pearlite carbon.*** If the steel is heated, a change occurs at the decalescence point and the pearlite becomes **martensite carbon** or "hardening carbon." Then, if the steel is allowed to cool slowly, the martensite changes back to pearlite at the recalescence point.

TEMPERING. This is done after hardening, and consists of reheating to some temperature below the critical temperature range followed by quenching.

Take the typical cases of lathe tools, punches, chisels, etc., made from medium- and high-carbon steels, which are forged in a red-hot condition and hardened by heating to, say, 750° C. (say, "cherry red" heat), followed by quenching of the cutting end. While this leaves the tool in its hardest and strongest condition, it also leaves it very brittle. The brittleness must therefore be reduced without, however, causing great reduction in hardness and strength. Tempering consists of reheating the steel to a certain predetermined temperature, and then quenching it again. To return to the lathe tool previously mentioned, the quenched (hardened) end is quickly polished with emery or stone and the heat from the shank

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* A simple and well-illustrated introduction to the microstructure of steel will be found in Vol. 3 of *Workshop Practice* (Pitman) and in *The Structure of Steel Simply Explained*, by Simons and Gregory (Blackie).

end of the tool allowed to travel along towards the cutting edge. The "temper colours" (oxidization tints which a bright metal surface assumes when heated) serve as a rough guide to temperature as they travel along towards the cutting edge, commencing with a pale straw and ranging to a dark blue. When the correct colour nearly reaches the end of the tool, the whole is quenched. A list of tempering colours is given. Tools such as milling cutters, lathe tools, etc., require maximum hardness without brittleness, whereas screwdrivers, cold chisels, etc., can be left considerably softer.

Colour	Temp. Deg. C.	Articles
Light straw .	230	Hammer faces, brass screwing dies, scrapers, light lathe tools, etc.
Dark straw . .	240	Drills, milling cutters, chasers, etc.
Brown . .	255	Taps, screwing dies, shear blades, reamers, etc.
Brown-purple .	270	Punches, twist drills, snaps, etc.
Light purple .	275	Axes, hot setts, press tools, etc.
Dark purple .	285	Cold chisels, planing cutters for softwood, etc.
Full blue . .	295	Circular saws for metals, screwdrivers, etc.
Dark blue . .	300	Springs, wood saws, etc.

The "colour-tempering" method just described is rather haphazard, and it is being superseded by tempering under pyrometric control in oil, salt, sand, and lead baths and also in furnaces in which the air is circulated by fans. After tempering, the pieces may be cooled rapidly or slowly, according to their composition.

ANNEALING consists of heating the steel to any predetermined temperature and allowing it to cool slowly. This definition necessarily lacks precision, because the treatment is modified according to the particular purpose in view.

The purpose of annealing may include one or all of the following—

1. To soften the steel for machining, stamping, etc.
2. To refine the grain and make the steel ductile, i.e. to reduce brittleness.
3. To relieve the hardness and internal stresses which may have been set up due to rapid cooling in previous hot working, e.g. forging, casting, etc.
4. To restore the crystalline structure which may have been upset by previous cold working.

The process consists of (*a*) heating the steel, (*b*) soaking it at this temperature, (*c*) cooling.

If the object is to make the steel soft for machining, there is no need to heat it into the upper critical range. Heating to just below the critical point and cooling slowly in air will give the desired result. Mild steel wires and sheets which are repeatedly cold-worked in manufacture are "**process-**" or "**close-annealed**" by heating to, say, 550–650° C. for several hours.

For "**full annealing**" of hypo-eutectoid steel (i.e. steel with a maximum carbon content of 0·9 per cent) the temperature is raised to just *above* the upper critical point, after which the steel is allowed to cool slowly in the furnace. This gives maximum refinement and also fulfils the other three objects of annealing. The high-temperature soaking is maintained long enough (in hours or days) to attain even heating throughout.

To prevent scale formation, especially on polished surfaces, the pieces annealed are sometimes packed in metal boxes containing some such material as powdered charcoal or slaked lime.

NORMALIZING. *Object*: To relieve the stresses and refine the crystal structure after the steel has been coarsened by previous hot working, e.g. welding, bending, etc.

This is usually carried out by slowly heating the steel to above the upper critical point and then allowing it to cool freely *in still air.*

B.S.S. No. S.3, relating to mild steel sheets, will repay study. The steel should be maintained at the required temperature for about 15 min.—the time depending upon the shape and form of the job—and the temperature should not exceed the upper critical point by more than 50° C.

Normalizing, properly done, will put the steel into a uniform unstressed condition, with a refined grain, so that it will later on respond satisfactorily to further heat treatment. It produces a somewhat finer crystalline structure than annealing and also improves the yield point and tensile strength; the ductility remains the same, although the reduction-of-area-per-cent value is raised. In the case of castings made of high-tensile steel, the ductility may be reduced.

Sometimes annealing for machineability is preceded by normalizing. Normalizing temperatures are usually higher than those used for annealing. Before machining mild steel it is often normalized, but it is more common to normalize *and* anneal before machining the medium- and high-carbon steels.

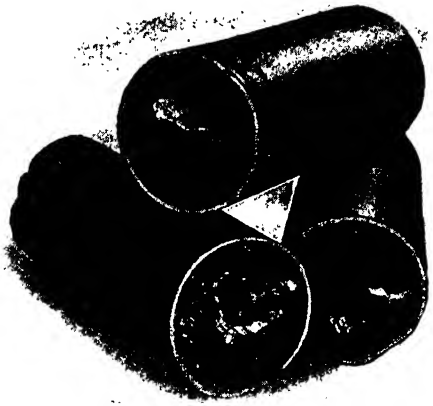


FIG. 36. TYPICAL FRACTURES IN CASE-HARDENED BARS

CASE-HARDENING. The object is to produce a steel with a hard surface to resist wear as well as a tough core ductile enough to withstand shock and resist breakage. Low-carbon steel (mild steel) objects can be given a high-carbon outer surface by heating them at about 900° C., i.e. above the upper critical temperature, while in contact with a carbon-rich material (solid, liquid, or gaseous). This carburizing mixture (commonly animal or wood charcoal, prussiate of potash, sal-ammoniac, etc.) forms carbon monoxide, which penetrates the case of the steel. The depth to which the carbon penetrates depends on the time of heating (say about 4 hours) but is not usually over $\frac{1}{16}$ in. (See Fig. 36, which shows typical fractures of case-hardened steel bars.)

After the carburizing operation the articles are heat-treated (*a*) to refine the core, (*b*) to refine and harden the case.

1. **Core Refining.** The carburized piece is heated to about 870° C. (just above the upper critical point of the core). After soaking, the article is quenched in water or oil.

2. **Refining and Hardening the Case.** This is done by quenching in water from a temperature of about 750–800° C. If a carbon case of about 0·9 per cent has been obtained, this temperature is just above the critical range for the case.

Tempering at about 150° C. may follow these operations to relieve quenching stresses.

Steels for case-hardening have a carbon content usually below 2 per cent, but slightly higher carbon contents are sometimes specified. Other elements most commonly added to case-hardening steels are nickel and chromium.

Typical Aero Case-hardening Steels. (*a*) 2S.14. A straight carbon. Used for camshafts, push-rod ball ends, etc. (*b*) 3S.15. A 3 per cent nickel. (*c*) S.82. A 5 per cent nickel-chrome used for reduction gears, etc.

The straight carbon steel, if properly heat-treated, will provide the hardest case. The others, owing to the presence of nickel, have stronger and less fibrous cores, offering greater resistance to shock loading.

Quick Case-hardening by Fitters, etc. The article to be case-hardened is heated to a medium red and dipped into a case-hardening compound, e.g. Kasenit No. 1, yellow prussiate of potash, potassium cyanide, or, in emergency, sugar. The article is then replaced in the fire and maintained at red heat for a few minutes, after which it is quenched in cold water. The article may be dipped into the compound three or four times, being maintained at red heat between each dip, and finally quenched as before.

NITRIDING. This is a new process of surface hardening whereby certain "Nitralloy" steels can be given a thin but extremely hard case at comparatively low temperatures without quenching.

The surface layers are enriched with nitrogen by packing the pieces in a sealed box through which ammonia gas is circulated, and the whole heated for 40–95 hours at 500° C. in a furnace. This is followed by cooling in the box. The "Nitralloy" steels contain about 1 per cent aluminium, 1·5 per cent chromium and 0·2 per cent molybdenum. If desired, parts of the work can be left soft by covering them with a coating of tin or solder. On aero work this surface-hardening process is carried out to a limited extent on crankpins and journals, inside of cylinder barrels, valve stems, etc., and other parts where local shock loadings do not occur.

PYROMETERS. For the accurate measurement of high temperatures various types of *pyrometers* are used, of which the most extensively employed are **thermo-electric pyrometers.**

The basic principle is the employment of two wires of dissimilar metals which are joined to form a complete electric circuit in which a current will flow if the junction of the wires is heated. The value of the e.m.f. depends on the temperature difference of the junctions and the metals used. If the two metals are respectively connected to a millivoltmeter and then placed in a furnace, the e.m.f., which varies with the temperature of the furnace, can be measured. Some arrangement must be made whereby direct readings in degrees may be taken either near to the furnace or at a place some distance away.

Optical Pyrometers. In these the intensity of the *light* from the hot body is compared with the intensity from some standard source. One type indicates the temperature by heating the filament of an electric lamp to the same *colour* as that of the incandescent body, the temperature of which is required. The consumption of current is indicated by a milliammeter, and the corresponding temperature determined.

Inspection of Heat-treated Steel Parts for Aero Work. Inspection Leaflet No. 407 requires that temperatures shall be measured by pyrometers, the hot junctions of which must be close to the parts undergoing treatment. All pyrometric installations are to be checked at least once a week and recalibrated (preferably by the makers thereof) at least annually. Plant, equipment, and methods used in connexion with heat treatment shall be to the satisfaction of the supervising inspector.

For the purpose of Leaflet No. 407 heat treatment is defined as a hardening (and tempering) process made necessary by the requirements of either a specification or an order for material. Inspectors engaged on inspection of heat-treated steel parts for aero purposes will find useful guidance in this leaflet. When the relevant specification includes definite requirements as to heat-treatment temperatures, these will usually be stated also on the release notes or material tests reports, and such requirements must be complied with.

HARDNESS TESTING. In mechanical testing it is usual to consider hardness as **resistance to indentation.** However, the word "hardness" is used with various meanings in engineering, e.g. in machine-tool work we think rather of *ability to cut.* Many readers will know that manganese steel is, speaking generally, impossible to machine in normal commercial machine tools, yet its resistance to indentation is low in comparison with that of the tools employed.

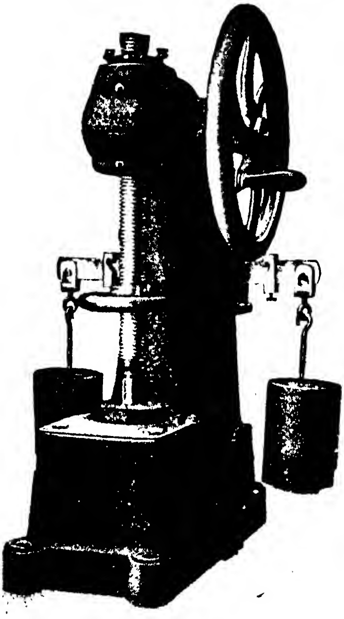


FIG. 37. BRINELL HARDNESS-TESTING MACHINE
(*W. & T. Avery, Ltd.*)

Many methods have been devised for testing hardness. Four will be considered here.

1. **The Brinell Test.** Fig. 37 shows a typical machine. The test consists of pressing, under a known load, a hardened steel ball into the material under test and measuring the average diameter of the

impression with the aid of a microscope. The spherical area of the impression or indentation is calculated from its diameter—

$$H = \frac{\text{Load}}{\text{Area}} = \frac{P}{\frac{\pi D}{2}\,[D - \sqrt{(D^2 - d^2)}]} \text{ kg./sq. mm.}$$

where P = load (kg.),
D = diameter of ball (mm.),
d = diameter of impression (mm.), measured microscopically.
H = hardness number.

This is an awkward-looking formula, and fortunately Brinell numbers are usually obtained from tables giving impression diameters and corresponding Brinell numbers.

For steel the diameter of the ball is usually 10 mm. and the load 3 000 kg., for copper the load is 1 000 kg., and for aluminium 500 kg. If other sizes of ball are used, the load is varied according to the relation—

$$P/D^2 = \text{a constant}$$

This relation depends upon the fact that indentations, made under such conditions, are similar. The ratios of P/D^2 for various classes of materials have been standardized by the B.S.I. (See *B.S.S. No.* 240, 1926.) The constant for iron and steel is 30, for copper alloys 10, for aluminium 5, for lead, tin, and metals of similar hardness 1.

For **thin samples** and for other special purposes, balls whose diameters are less than 10 mm. are now being used. The diameters of these balls recommended by the B.S.I. are 5 mm., 2 mm., and 1 mm.

The **time of loading** is important, especially with soft materials. It should not be less than 15 sec. for steel, but should be 30 sec. where the value which is used for P/D^2 is 10 or less.

Piling-up of metal round the edge of an impression (Fig. 38 (*a*)) indicates a low capacity for hardening by deformation.

Sinking (Fig. 38 (*b*)) indicates the ability for work-hardening.

Brinell Numbers and Tensile Strength. It is interesting to note that the approximate tensile strength (tons/sq. in.) of steels can be obtained by multiplying the Brinell number by 0·23 for annealed conditions and by 0·21 for quenched and tempered steels.

Very Hard Metals. The Brinell test is unsuitable for very hard materials, as errors arise causing low values due to (1) the spherical shape of the indenter, and (2) flattening of the ball. The B.S.I. recommendations on the Brinell tests will repay study by those called upon to use this method.

Brinell Tests on Aero Work. Detailed instructions and valuable hints are given in Inspection Leaflet No. 406.

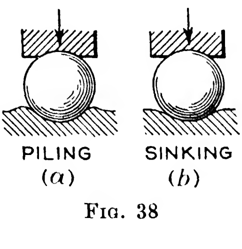


Fig. 38

Pocket Type of Brinell Testing Machine. A pocket type of Brinell testing machine is the *Rudge-Whitworth Auto-Punch,* designed to meet the need for rapidly testing awkward pieces that cannot be placed under the standard Brinell machine. The punch is fitted with a steel ball $\frac{3}{16}$ in. dia., and the mechanism to deliver the blow consists of releasing a spring-loaded weight within the handle of the punch.

Diamond Brinell Hardness Test. The principles involved are practically identical with the ordinary Brinell method, except that the ball is replaced by a diamond pyramid. A predetermined load is impressed at a point upon the specimen. The ratio of the impressed load to the area of the resulting indentation gives the hardness number.

The Vickers and Brinell hardness numbers on steel are practically identical up to a hardness of about 300. At higher hardness values the Brinell falls progressively lower than the Vickers number, and is not reliable above about 550

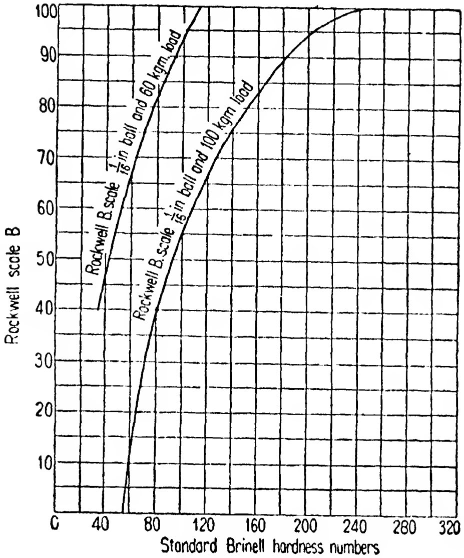


Fig. 39. Conversion to Standard Brinell Hardness Numbers of Rockwell *B* Scales

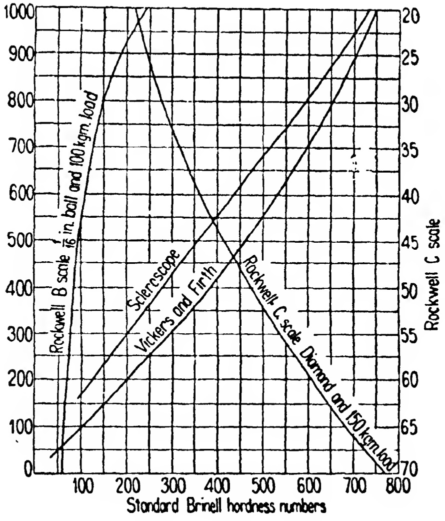


Fig. 40. Conversion to Standard Brinell Hardness Numbers of Rockwell (*C* and *B* Scale), Vickers', and Firth's Diamond Hardness Numbers, and Shore Scleroscope

to 600 Brinell hardness, even with specially hardened balls. The irregularity is caused by flattening of the steel ball under the heavy local loads required for testing hard materials, whereas the diamond shows no distortion. See the notes on the Firth Hardometer.

2. **Rockwell Hardness Test.** The Rockwell test is ideal for carrying out rapid routine tests on finished jobs. It measures hardness by determining the depth of penetration of a *penetrator* into a specimen under certain fixed conditions. The penetrator may be either a steel ball or a diamond sphero-conical penetrator. The hardness number is related to the depth of indentation, and the harder the material the higher the number. First a minor load of 10 kg. is applied to take out any slack in the machine and the indicator. This causes an *initial penetration.* The dial gauge is then set at zero on the black-figure scale and the major load applied. Where a steel ball is used, this major load is usually 60 kg. or 100 kg. The diameter of the ball penetrator is $\frac{1}{16}$ in. normally, but for soft materials it may be up to $\frac{1}{8}$ in. The load employed for a diamond sphero-conical penetrator is usually 150 kg. In more accurate laboratory testing the depth of indentation is measured by means of a microscope.

There are a number of *Rockwell scales* applicable to different circumstances and depending on (1) the load and (2) the type of penetrator employed. The letters *C* and *B* in Rockwell scales indicate respectively—

1. *C.* Tests with a conical diamond penetrator having a rounded point and a 150 kg. major load;
2. *B.* Tests with a ball penetrator of $\frac{1}{16}$ in. dia. and a 100 kg. major load.

Scales *A*, *E*, *D*, *F*, *G* relate to tests under entirely different conditions. Rockwell-Brinell conversion tables (necessarily only approximately exact) are given in various engineering handbooks.

Rockwell Tests on Aero Work. Many useful hints are given in Inspection Leaflet No. 406, wherein is also contained a graph relating Brinell numbers with Pyramid Hardness numbers.

3. **The Vickers Machine** is very suitable for polished and hardened components and employs a diamond-pointed penetrator of square-based pyramidal form. It does not readily deform, and gives geometrically similar impressions under different loads, which are applied automatically from 5 to 120 kg. The load is applied without inertia for a predetermined time and is then automatically released. A microscope can be swung immediately over the square impression, the diagonals of which are measured between knife-edges and the reading taken from a digit counter. Fig. 41 shows the appearance of the impression as seen through the microscope. The contact area of the impression divided into the load gives the Vickers pyramid number (V.P.N.).

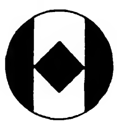


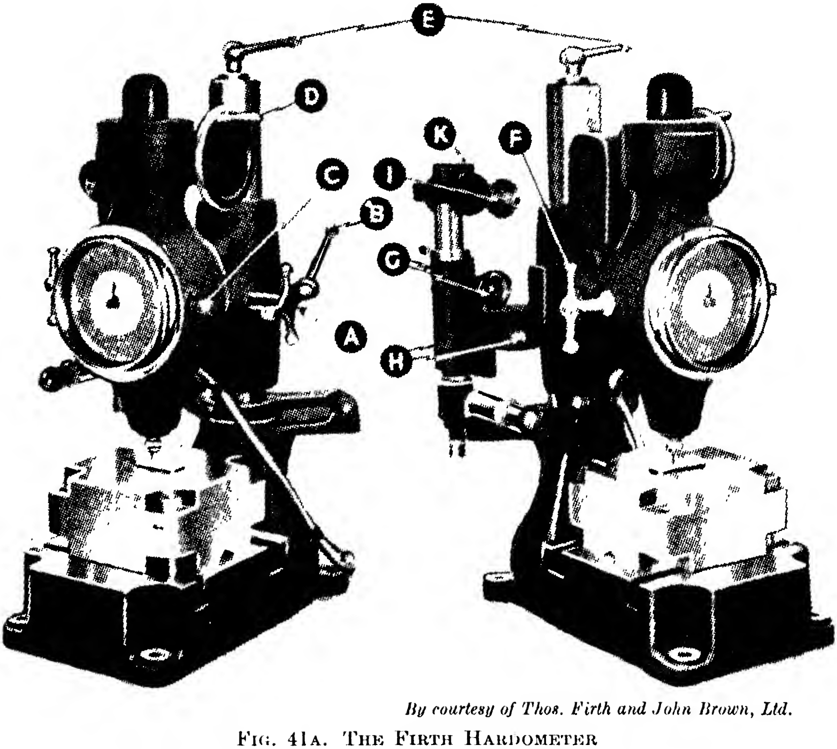
FIG. 41
APPEARANCE OF IMPRESSION

Brinell and Vickers hardness numbers are almost identical up to a hardness of number of 300. Over 600 the Brinell number is not so reliable.

4. **The Shore Scleroscope.** This instrument, introduced by Mr. A. F. Shore in 1907, measures hardness of dies, rolls, gears, etc., by measuring the rebound by a small diamond-tipped hammer, which is allowed to strike the material under test. The hammer weighs about

$\frac{1}{12}$ oz. and is allowed to fall freely through a height of about 10 in. down a glass tube graduated in 140 equal parts. The height of the first rebound is taken as the index of hardness.

When making a test the instrument should be as nearly level as possible as indicated by the plumb bob on the right side of the tube barrel. The tripod screws shown in the illustration (Fig. 42) facilitate this levelling. The plunger hammer is sucked up and then released by pressing the rubber bulb. The diagram is reproduced by courtesy of the Coats Machine Tool Co. Ltd.



By courtesy of Thos. Firth and John Brown, Ltd.

FIG. 41A. THE FIRTH HARDOMETER

Operating Instructions. After polishing a small surface on the specimen, place it beneath the indenter, making sure that it rests firmly on the anvil of the machine. Lower the head of the machine by means of the handwheel (A) until the indenter is within about $\frac{1}{4}$ in. of the specimen, and then lock the head in position with the lever (B). Rotate the dial by means of the knurled knob (C) until the graduation of the required load appears immediately behind the pointer on the scale. Make sure that the power supply is connected. Turn the loading handwheel (D) rapidly till the small central pointer reaches the graduation "2" and then slowly until "O" is reached—At this point an electrical trip gear prevents further winding—*Hold in this position for* 15 *seconds*. Turn the handwheel (D) back to remove the load and to raise the indenter clear of the specimen, BUT DO NOT TOUCH THE SPECIMEN. Loosen the clamping spindle (E), swing the microscope head over against the stop by means of the handle (F) where it will come to rest immediately over the impression. Focus the microscope by means of the milled wheels (G), and then bring one side of the impression up to the fixed knife-edge in the eyepiece, using the small thumbscrews (H). Turn the knob (I) on the right of the special micrometer eyepiece until the movable knife-edge just touches the other side of the impression, and read off the diameter (in microns) from the counter (K).

5. **The Firth Hardometer,** marketed by Thos. Firth and John Brown, Ltd., Sheffield, acts on the principle of the Brinell test in which a hard steel ball or diamond indenter is pressed under a predetermined load into the surface to be tested. The size of the resulting impression provides a measure of the hardness and the actual value is obtained from tables provided with the machine. The load is applied through a calibrated spring and the impression is measured by means of a microscope. See Fig. 41A.

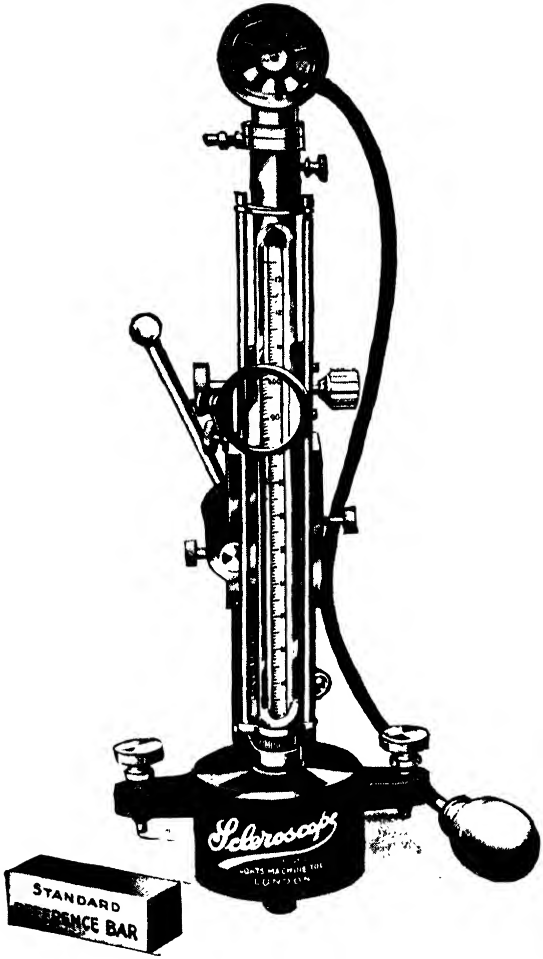


FIG. 42. THE SHORE SCLEROSCOPE
(*Courtesy of Coats Machine Tool Co. Ltd.*)

For testing hardened steel of over 550 it is usual to employ a diamond indenter (B.S.I. standard angle of 136° between opposite faces) which on these machines is interchangeable with the ball indenter. Diamond indenters are essential when testing hard nitrided and tool steels, etc. Operators should be careful to distinguish between *Diamond Hardness Numbers* and *Brinell Numbers* (obtained by the usual method with a steel ball). A graph giving the approximate conversion from the one to the other is included with each machine. For diamond impressions the B.S.I. recommend that the thickness of material for test should be at least 10·5 times the depth of the impression. On thin sections a good criterion is given when the underside of the specimen shows no trace of the impression. Probably the most commonly used Firth Hardometer is the 30 Kg. fixed load model, but the variable load model can be used to cover the whole range of hardness testing requirements.

On **aero inspection work** where a minimum or maximum Brinell or Diamond Pyramid number is specified the test should be made on Brinell machines complying with B.S.S. No. 240, or Diamond Pyramid hardness testing machines complying with B.S.S. No. 427. (See Inspection Leaflet No. 406.)

In other cases, where tests are required solely to check the uniformity of the material (as in Inspection Leaflet No. 407), Rockwell and Avery direct-reading hardness testers may also be used.

Cloudburst Process. A process in which an object is bombarded with a shower of small hardened steel balls. As a means of hardness testing, the process comprises dropping the balls from a height so regulated that only those portions not quite hard enough will be indented. If only a comparatively small number of balls is employed, the separate indentations can be measured. The process can also be used as a means of work-hardening the surface of steel parts to give them a specially hard surface.

COMPARISON OF HARDNESS VALUES

Material	Brinell		Vickers Pyramid No.	Rockwell Scale		Shore
	Impression dia. mm.	No.		*C*	*B*	
Soft brass	—	60	61	—	—	—
Mild steel	5·20	131	131	—	74	20
Soft cast steel	3·95	235	235	22	99	34
White cast iron	3·00	415	437	44	114	57
Nitrided surface	2·25	745	1 050	68	—	100

CHAPTER VI

THE ELEMENTS OF MEASUREMENT

THE evolution of national standards of measurement and the toilsome preparation of standard and secondary bars for reference were long and tedious processes. Linear dimensions, e.g. lengths, widths, thicknesses, diameters, etc., comprise the greater part of the measuring work done in the shops, and these have brought into being a great variety of measuring instruments.

The Imperial Standard Yard. This is defined by Act of Parliament as follows—

The straight line or distance between the centres of two gold plugs in a bronze bar when the bar is at 62° F. and supported by bronze rollers placed under it in such manner as best to avoid flexure of the bar and facilitate its free expansion or contraction.

One-third of the Imperial Standard Yard shall be a FOOT and the twelfth part of such foot shall be an INCH.

The Metre. The standard metre as established by French law consists of the distance between the two ends of a bar of platinum and iridium, 90 parts of the former to 10 parts of the latter. The length was derived from the report of a commission appointed by the French Government, which recommended a measure derived from a quadrant of the earth's meridian, divided into ten million equal parts, the metre being a subdivision. The bar is standard only at 0° C.

The millimetre is a commonly used unit in engineering work, and is the one-thousandth part of the metre.

We can measure by *direct observation* as, for instance, when a dimension of an object is determined by placing it in contact with a graduated rule, or when the surfaces of a piece of work are brought into contact with surfaces of a gauge, the latter embracing the former, or vice versa. Of these there are two great groups—those in which the dimension is rigidly controlled and permanent, as in the fixed gauges, and those where it is capable of variation, as in the common caliper, the beam calipers, the micrometer and the standard measuring machines.

Measurement by Sight and by Touch. The fixed gauges have long superseded the common rule and calipers simple depth gauge, etc., for precision work, yet many of the finest measurements are still taken by direct readings of divisions. This is possible because we can use the micrometer or the vernier to supplement the main element, viz. the screw of fine pitch, or the graduated rule. A difference of 1/100 in. is difficult to measure on a rule, but from 1/10 000 to 1/50 000 in. can be detected on other forms, and still finer dimensions on some measuring machines.

Rules. These are nowadays made to great accuracy, practically all (both light and heavy) being spring tempered. Many are flexible or semi-flexible. Stainless steel rules are achieving a foothold. A variety of graduations has become available, e.g. 64ths, 32nds, 16ths, 8ths, and 100ths, 50ths, 20ths, 10ths.

A usual length is 12 in., but rules are readily obtainable from 1 in. to 48 in. long. The flexible rule, 6 in. long, is sold in large numbers and can be carried in the waistcoat pocket. It is extremely handy for measuring on a curved surface.

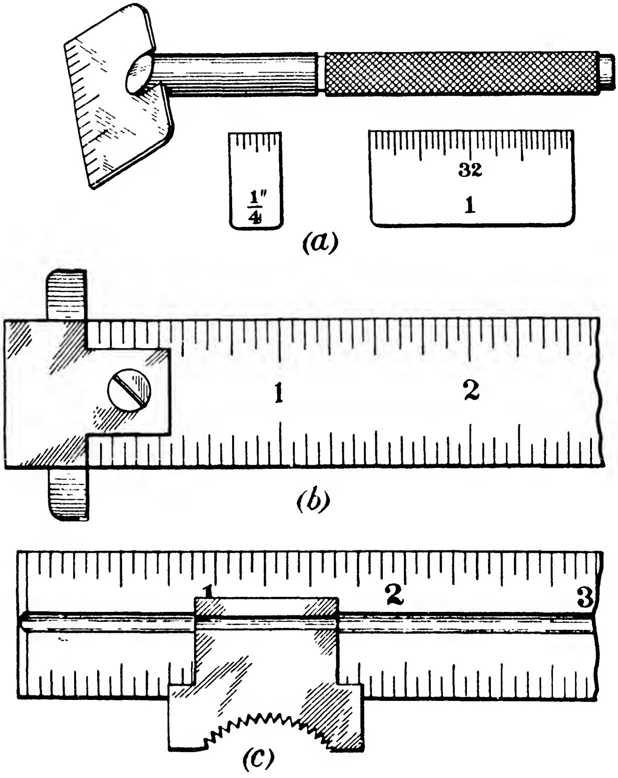


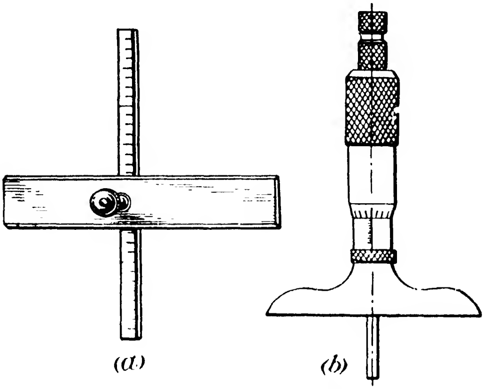
Fig. 43. (*a*) Rule Holder, (*b*) Hook Rule, (*c*) Rule with Thumb Slide

Rule Holders (Fig. 43 (*a*)). Short tempered steel rules may be provided with holders capable of retaining the rules at an angle of 30° as shown. A slight turn of the knurled handle against a spring plunger locks the rule. These holders prove useful where it is inconvenient to use an ordinary rule, as in machining operations where there are grooves and short shoulders to be turned, or when measuring a recess or keyway.

Adjustable Hook Rule (Fig. 43 (*b*)). Hook rules are made in various designs and are useful when measuring (1) against a shoulder, (2) width of a flange or collar, (3) inside length of a hub, etc. They can also be used when setting inside calipers. The hook shown in the illustration is hardened and tempered and can be adjusted to be short or long in connexion with any one of the graduations on the rule. By a simple turn of the eccentric stud it can be removed altogether.

Rule with Thumb Slide (Fig. 43 (*c*)). The slide is adjustable. Thus the rule is useful for measuring width of flanges, collars, etc., or for measuring against a collar. The slide may be used on either edge of the rule.

Depth Gauges. Typical of the many uses of these are (1) measuring the depth of blind holes, recesses, etc., (2) measuring heights of spigots, registers, etc. In its simplest form a depth gauge consists of a head (the under side being a plane surface) and an adjustable rod or blade passing through it at right angles. Many of these simple gauges have the rods graduated for recording the depth or height measured. The head is first placed across the hole and the blade lowered until it "touches bottom," when the set screw is tightened.



(*a*) (*b*)

FIG. 44. DEPTH GAUGES

Fig. 44 (*a*). Here is shown a *simple depth gauge* with a graduated rule which can be used clamped close to the end or used in the centre.

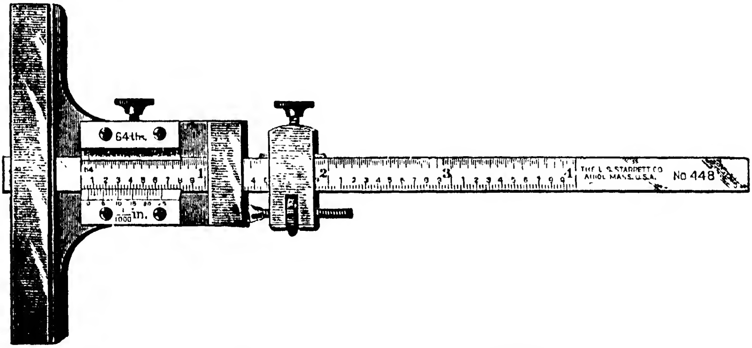


FIG. 45. VERNIER DEPTH GAUGE

(*Courtesy of L. S. Starrett Co.*)

Fig. 44 (*b*). *Micrometer Depth Gauge.* This provides for measurements to one-thousandth of an inch from 0–3 inches. Each gauge has three measuring rods with hardened and lapped ends. These can be inserted through a hole in the screw. The base is hardened, ground and lapped. Many rods are made with their ends slightly concave.

Fig. 45. *Vernier Depth Gauge.* The head is hardened, ground and lapped. The graduations and vernier scales enable measurements to be taken to 1/64 in. or 1/1 000 in.

Fig 46. Fixed Depth Gauges. The depth gauges shown previously are suitable for use on components made singly or in small numbers. For mass-produced parts intended to be interchangeable, "go" and "not go" pin and plate fixed depth gauges are suitable, although for work with close limits specially designed gauges with indicator attachments are often considered necessary.

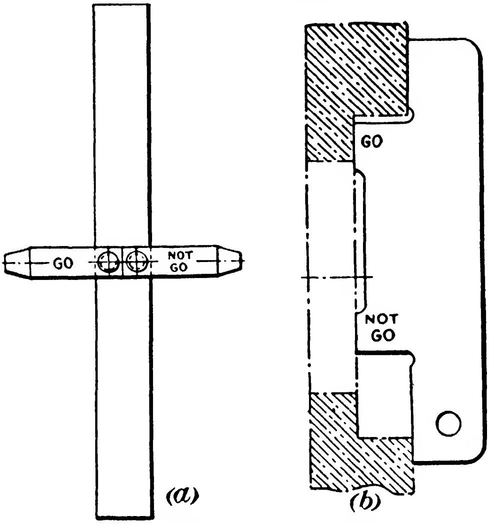


FIG. 46. FIXED DEPTH GAUGES

The gauge shown at (*a*) is suitable for testing a hole or recess with a "blind" or flat bottom. The ends of the pins are ground square with the datum faces of the rectangular strip. The "go" pin represents the low limit of depth, whilst the "not go" represents the high.

The plate gauge shown at (*b*) is rather similar in principle, its design and proportions depending upon the shape of the job being examined. When using such a gauge it is obvious that care must be exercised in seeing that the "go" face is clear of the component when trying the "not go" face.

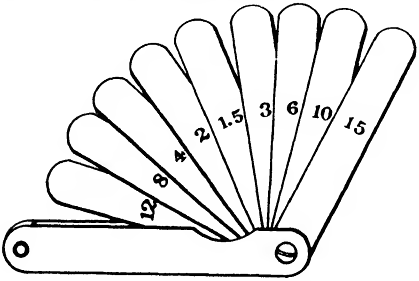


FIG. 47. THICKNESS OR FEELER GAUGE

Leaf Gauges. These comprise a very large range of fixed gauges. They consist of an assembly of steel leaves, having, in some cases, the edges shaped to test thread profiles, radii, fillets, etc. (See, for instance, Fig. 98.)

Fig. 47 shows a pocket **feeler gauge** or **thickness gauge** ("feelers") used to test accuracy of fit. A "not go" snap gauge, for instance, may pass over the work and by inserting a feeler blade of suitable thickness, found by trial, the degree of inaccuracy can probably be found. The exact thickness, usually in thousandths, is marked on each leaf and the leaves can be used singly or in combination. Feelers are useful when testing the accuracy of scraped surfaces in contact, finding clearances between worn machine parts, etc. The numbers on the leaves in Fig. 47 represent thickness in thousandths of an inch.

When making form tools, etc., it is essential to be able to gauge both male and female radii and we are enabled to do this, satisfactorily enough for many purposes, by means of **fillet or radius gauges,** sold by all tool factors either in leaf form (Fig. 48) or as a number of thin plates supplied on a split ring.

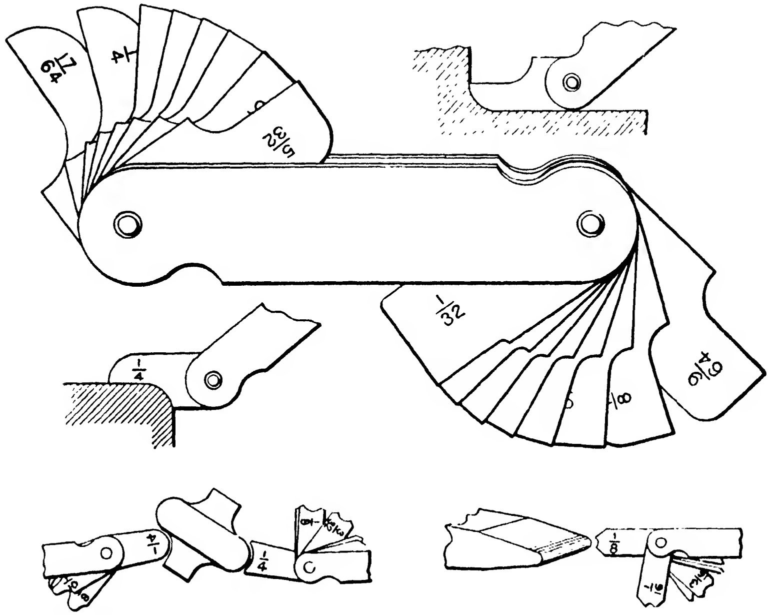


Fig. 47. Fillet or Radius Gauges

Special-purpose Profile Gauges or Templets. For checking a machined profile a *form* or *profile sighting gauge* may be used. (See Fig. 49.) If the profile of the gauge has a knife edge it can be applied to the work and viewed against a light or a white background. In Fig. 50 is shown a useful templet for ascertaining whether an aero-engine valve has become distorted under the tulip. Special depth gauges are used to ascertain if the valve stem has stretched. In Fig. 51 is shown a profile limit gauge for testing machining of fillister headed set screws.

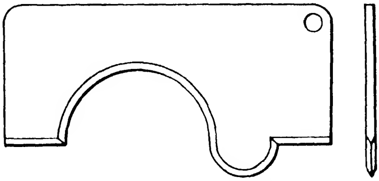


Fig. 49. Profile Gauge or Templet

The Dial Test Indicator. This handy instrument has grown greatly in popularity in recent years both for production and inspection measurement. Its uses are legion, e.g. checking plane surfaces for parallelism and thickness, end floats or clearances, parallelism of shafts, bars, rods, concentricity of holes, etc.

There are many excellent models obtainable. We shall now particularly describe the well-known Matrix dial gauge manufactured by the Coventry Gauge and Tool Co. Ltd., as this represents the best British practice.

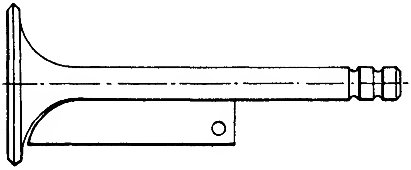


FIG. 50. TEMPLET GAUGE

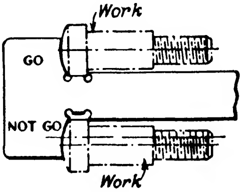


FIG. 51. SIMPLE PROFILE LIMIT GAUGE

These gauges conform to N.P.L. standards. The rack, pinions and pivots are of rustless steel, the totally enclosed die cast case being heavily nickel plated and fitted with a detachable lug at the back. The stem is hardened and ground, sliding in a phosphor bronze bush cast into the body of the case. All gauges are fitted with detachable ball tipped contact points as standard. A setting ring is provided on all models enabling the dials to be locked in any position. Unless ordered to the contrary these gauges are supplied with a light movement for *hand measurement*. Heavier movements are generally preferred for *machine use* and are obtainable at small extra cost.

Illustrations in this chapter represent *any* dial gauges—not necessarily particular makes.

Typical Uses (Fig. 52 (*a*) **).** Dial gauge set in tool post holder. This holder can be secured in the tool post of a machine tool, e.g. lathe, shaper, planer, etc., so as to test the parallelism or concentricity of the work.

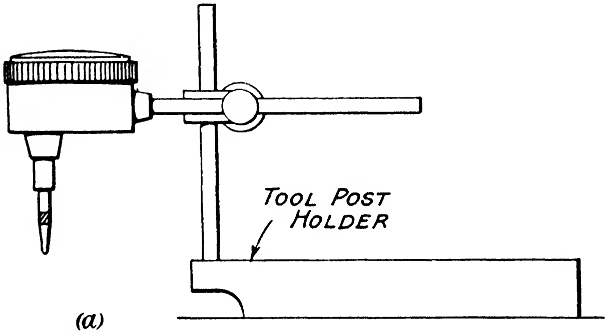


FIG. 52 (*a*). DIAL GAUGE IN TOOL POST HOLDER

Fig. 52 (*b*). Dial gauge used with surface gauge for checking plane surfaces and for checking a number of machined surfaces for size, alignment, or parallelism. The gauge can be set to zero by means of slip and thickness gauges. An average measuring range for these dials is about 0·2 in. to limits of 0·0005 in. If the knurled outer ring is twisted by hand the dial may be moved to bring the zero mark into any position relative to the pointer.

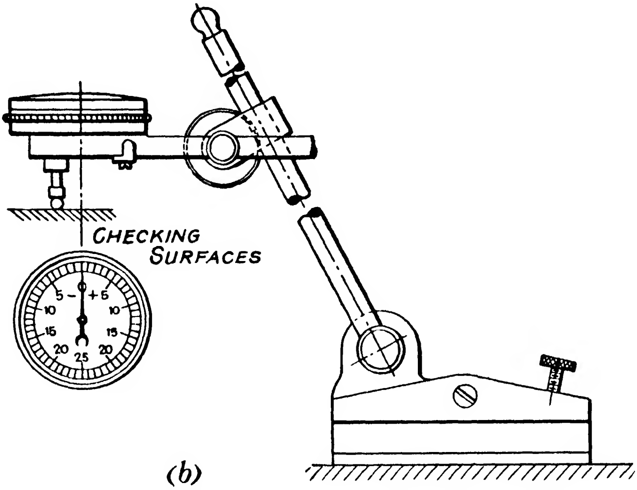


FIG. 52 (b). DIAL GAUGE USED WITH SURFACE GAUGE

Fig. 53. Dial gauge with surface plate. This shows a somewhat similar application, the gauge and surface plate being used as a comparator for testing flat or round components. If a large surface plate is used two or more dimensions on the same component can be checked by using extra standards and dials.

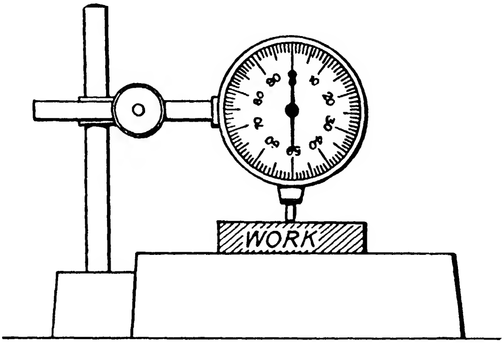


FIG. 53. DIAL GAUGE USED WITH SURFACE PLATE

The Starret Universal Dial Test Indicator (Fig. 54). With the contact points *D* and *E* any exterior surface may be tested as in cutters, racks, etc., whereas the contact point *C* with its smaller radius and diameter should be used only on plane surfaces. By bringing the contact point against the work with just enough pressure to give the hand one complete turn, then setting it at 0 an opportunity is given for one full revolution of the hand to right or left of 0, showing a rise or drop in the work and the amount of variation. A valuable feature is the adjustable dial. By turning the knurled rim the dial may be instantly moved to bring the 0 mark to any point desired in relation to the hand. Each indicator is fitted with three hardened contact points for different classes of work. The special tool-post holder and sleeve are useful in lathe work. The clamp *G* permits attaching the indicator to large lathe and planer tools, milling arbors, etc. The attachment *F* adapts the indicator for testing the insides of bored holes.

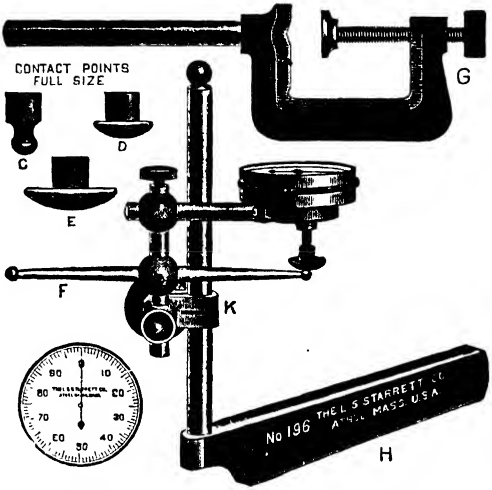


FIG. 54. STARRETT UNIVERSAL DIAL TEST INDICATOR

Hints on Mounting and Using Dial Gauges or " Clocks." Many of these read to thousandths of an inch over a range of half an inch or thereabouts. Others read in ten-thousandths of an inch over a shorter range. Sometimes they are mounted on ¼ in. dia. steel rods which, if used in long lengths, are apt to deflect or spring. The plunger of the instrument moves against the pull of a spring, which turns the pointer through a rack and pinion and two pairs of spur wheels. A clock mounted at the end of a long rod may fail to show any needle movement when it should do so. This happens when less force is required to bend the rod than to move the plunger against the pull of the spring and the friction and inertia of the internal multiplying mechanism. Dial gauges therefore should be mounted on rods of substantial diameter without unnecessary overhang.

Mercer Dial Gauges. Mercer dial gauges and accessories are well known to most inspectors as dependable British-made precision instruments. They are marketed in a range of types and designs by Messrs. J. E. Baty & Co. Ltd., 39 Victoria Street, London, S.W.1, from whom illustrated particulars are obtainable.

Most of them are supplied with back lugs for attachment to solid and sturdy fitments, thus obviating the tendency of the gauge to spring when mounted on a slender rod, as mentioned in the preceding paragraph. On the Mercer comparators, for instance, the dial gauges are attached to substantial cast-iron brackets; whilst on the Mercer dial test indicators the dials are attached to ½ in. diameter steel rods. The majority of the Mercer dial gauges are not of the type with the measuring plunger at the back.

CHAPTER VII

MICROMETERS AND VERNIERS

THE MICROMETER. This is also called a micrometer screw gauge or micrometer caliper gauge. Whilst a skilled man can use a pair of calipers to such advantage as to be able to measure and compare to within 1/64 in. to 1/100 in., the provision of a micrometer screw gauge enables him to measure to the 1/1 000 in., or even to the 1/10 000 in. with ease. Let us discuss the principles underlying the construction of a simple micrometer (as the device is shortly described) arranged so as to measure to 1/1 000 in.

The visible parts of a typical inexpensive micrometer are clearly lettered and named in Fig. 55. The following points should be observed.

General Description. The spindle C is fastened to the thimble E, so that when we rotate E we also rotate C. But the part of the spindle C which is concealed within D and E is threaded to fit a nut in the frame A. Thus, the frame A being held stationary, and the thimble E rotated between thumb and forefinger, the end of the spindle C advances or recedes from the anvil B. The article to be measured is placed between the anvil B and the end of the spindle C. Its measurement is read from the lines and figures on the sleeve and thimble.

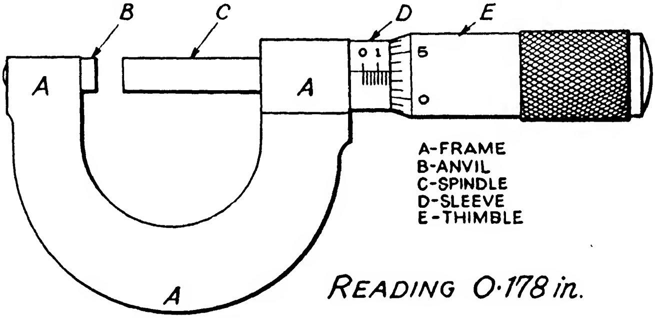


FIG. 55. 1 IN. MICROMETER OF SIMPLE DESIGN

The Spindle and Screw. We have already seen that for one rotation of a threaded piece through a stationary nut we have an axial advance equal to the pitch of the thread. Now the nut within A, as well as the threaded spindle on C, is screwed 40 threads per inch. Its pitch, then, is 1/40 in. = 0·025 in. It will now be clear that for one revolution of the thimble E, the spindle C moves ***axially***, i.e. in the direction of its axis or centre-line, through 1/40 in. or 25/1 000 in. or 0·025 in.

Sleeve. Now let us examine the graduation of the sleeve and the thimble. The sleeve D is marked with 40 lines to the inch, each tenth being separately marked and numbered so that tenths and fortieths clearly stand out. When the micrometer is screwed home (or closed) the bevelled edge of the thimble coincides with the line marked 0 on the sleeve, and the 0 line on the thimble coincides with the horizontal line on the sleeve.

Thimble. The bevelled edge of the thimble E is marked in 25 divisions—every fifth line being numbered. As a complete rotation of E causes an axial movement of C through 1/40 in., so 1/25 of a revolution of E will cause an axial movement of 1/25 × 1/40 = 1/1 000 in. or 0·001 in.

To Read the Micrometer (Fig. 55). Place the object to be measured between *B* and *C*. Lightly screw down *E* upon it. Then observe—

		In.
(*a*) Complete tenths on sleeve	1	0·1
(*b*) Add complete fortieths on sleeve	3 × 0·025	0·075
(*c*) Add the number of the line (on the bevelled edge of the thimble) which coincides with the horizontal line on the sleeve. Remember that the lines and numbers on the thimble count 0·001 in. each	3 × 0·001	0·003
	Complete reading	0·178

Further Settings (Fig. 56). Further micrometer settings are shown in Fig. 56 *a*, *b*, *c*, *d*. The reader should check the following readings—(*a*) 0·241, (*b*) 0·1, (*c*) 0·131.

Micrometers Graduated for Metric Measure. Micrometers designed to measure to the fractional part of a millimetre are read with facility by readers who have mastered the foregoing matter.

The pitch of the screw must first be discovered. It is generally either 1 mm. or ½ mm. The thimble is graduated so as to be able to read to one hundredth part of a millimetre.

THE VERNIER. Pierre Vernier (1580–1637) invented an auxiliary scale, or mechanical attachment to a scale, the use of which enables us to read to the very smallest divisions of a graduated scale and to a great extent does away with the possibility of errors in estimation which are bound to arise through what may be termed the "personal equation."

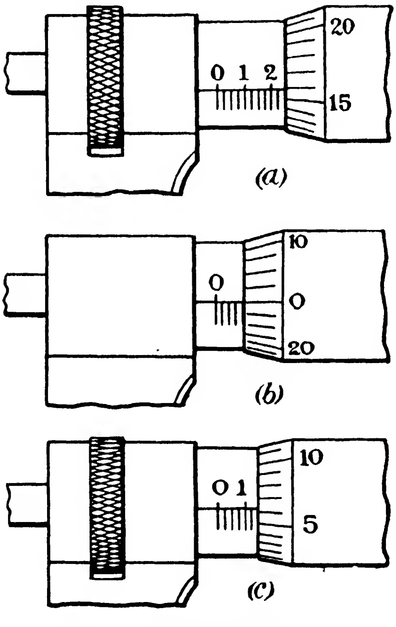


Fig. 56. Micrometer Settings

For the accurate determination of angular position a vernier attachment is indispensable in mountings of telescopes, theodolites, sextants, etc., also in barometers, cathetometers and scientific instruments for the measurement of length, e.g. comparators.

In the engineering world verniers are largely employed on caliper gauges which enable measurements to be taken to precision limits and so helps to render possible the mass-production of interchangeable parts.

The Hundredth Vernier (Fig. 57 (*a*)). First we have the main scale graduated in inches and tenths of an inch. Below it we have the auxiliary or vernier scale. The latter is divided into 10 equal parts and its total length is 0·9 in. as measured on the main scale.

Thus,

each division on the main scale $= \frac{1}{10} \times 1$ in. $=$ 0·1 in.
,, ,, ,, ,, vernier ,, $= \frac{1}{10} \times 0{\cdot}9$ in. $=$ 0·09 in.

Observe, (1) the first line on the vernier scale has dropped back one hundredth of an inch, i.e. 0·01 in., from the first line of the main scale,

(2) the second line on the vernier has dropped back 0·02 in. from the second line of the main scale,

(3) take any line on the vernier scale. Note its number. It has dropped back that same number of hundredths from or behind the line having the same number on the main scale.

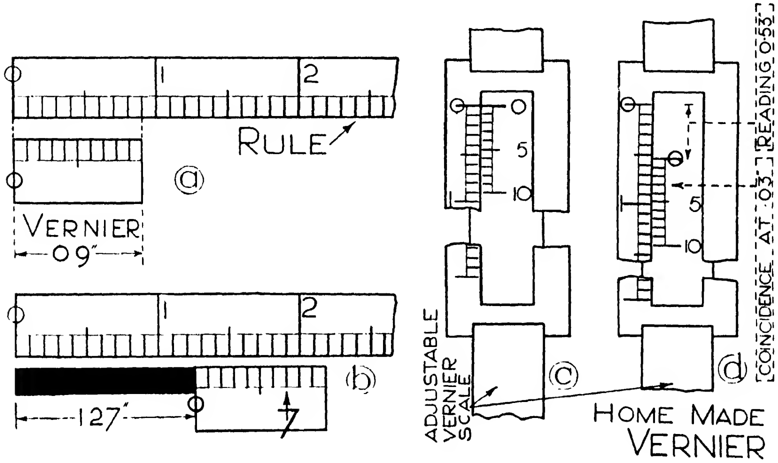


FIG. 57. A HUNDREDTH VERNIER

To Read the Hundredth Vernier (Fig. 57 (*b*)) we have to determine the number of inches, tenths, and hundredths the 0 mark on the vernier scale is from the 0 mark on the main scale.

		In.
(*a*) First read complete inches . . .	1	= 1·0
(*b*) Next read complete tenths . . .	2 × 0·1 . .	= 0·2
(*c*) Next observe what line on the vernier coincides with a line on the main scale. Bear in mind that each division on the vernier counts as $\frac{1}{100} = 0{\cdot}01$ . .	7 × 0·01 . .	= 0·07
	Actual complete reading	= 1·27

Useful Hints. (1) The graduations on the main scale are in inches and tenths. They merely enable us to read in inches and tenths. The hundredths are read from the vernier scale.

(2) Always read coincidence from the vernier; never from the main scale.

Simple Home-made Vernier (Fig. 57 (*c* and *d*)). A simple model vernier such as can be made at home by a beginner is shown in the illustration. Both the main vernier and the adjustable vernier scale can be cut out from stout drawing paper or thin Bristol board. The adjustable vernier scale passes through two slots in the framework of the main scale, in which it is an easy fit.

Readings (*c*) 0, (*d*) 0·53 in.

The Sixty-fourth Vernier (Fig. 58). Vernier caliper gauges designed to read in inches, eighths, and sixty-fourths of an inch are commonly employed in engineering practice. In Fig. 58 the usual arrangement is clearly shown. The main scale is divided into inches and eighths of an inch. The vernier scale is $\frac{7}{8}$ in. in length and is divided into eight equal parts. It follows that each of these parts on the vernier scale is less than $\frac{1}{8}$ in. by $\frac{1}{64}$ in.

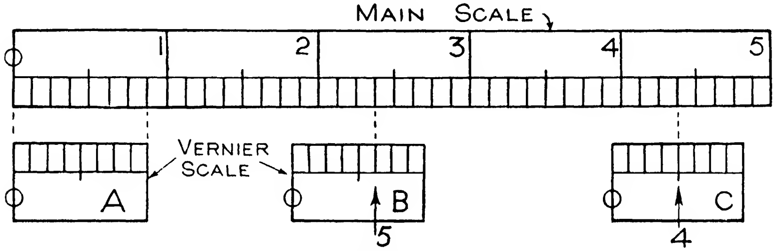


FIG. 58. A SIXTY-FOURTH VERNIER

To Read the Sixty-fourth Vernier we have to determine the number of inches, eighths and sixty-fourths the 0 mark on the vernier scale is from the 0 mark on the main scale.

Vernier in position B		In.
(*a*) First read complete inches	1	1
(*b*) Next read complete eighths and convert this reading into sixty-fourths	6	$\frac{48}{64}$
(*c*) Next observe what line on the vernier coincides with a line on the main scale. Bear in mind that each division on the vernier counts as $\frac{1}{64}$ . . .	$5 \times \frac{1}{64}$	$\frac{5}{64}$
Complete reading .		$1\frac{53}{64}$

Vernier in position C		In.
(*a*) Complete inches	(3)	3
(*b*) Complete eighths	(7)	$\frac{56}{64}$
(*c*) Complete sixty-fourths (shown by vernier)	(4)	$\frac{4}{64}$
Actual complete reading		$3\frac{60}{64} = 3\frac{15}{16}$

The reader will note that the written work for reading *C* is shorter than that for *B*. After a little practice he should be able to dispense altogether with this tabulation and take readings directly from the vernier.

The Columbus-type Vernier (1/128) (Fig. 59). The main scale is graduated in inches and sixteenths. The vernier slide is $\frac{7}{16}$ in. long and is divided into 8 equal parts. Thus 8 divisions on the vernier fall back

$\frac{1}{16}$ in. from 8 divisions on the main scale. Therefore 1 division on the vernier falls back $\frac{1}{16} \div 8 = \frac{1}{128}$ in. Thus we may read to $\frac{1}{128}$ in. on the vernier scale. Whilst $\frac{1}{128}$ in. is not, at first sight, a very practical unit,

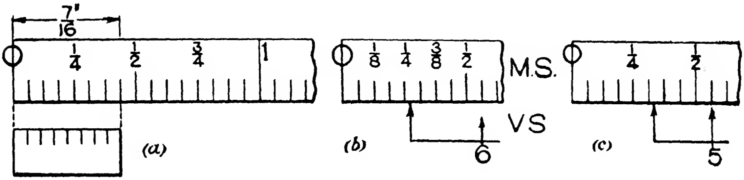


Fig. 59. Columbus-type Vernier

Reading (*b*)

Main scale (M.S.) $= \frac{1}{4}$
Vernier scale (V.S.) $= \frac{6}{128}$ } Sum $= \frac{19}{64}$ in.

Reading (*c*)

Main scale (M.S.) $= \frac{5}{16}$
Vernier scale (V.S.) $= \frac{5}{128}$ } Sum $= \frac{45}{128}$ in.

it comprises "half a sixty-fourth," and thousands of verniers of the "Columbus" type are graduated in this way. Two specimen readings are given for study.

The Thousandth Vernier

1. Fig. 60. In which 25 divisions on the vernier scale equal 24 divisions on the main scale.

This is the commonest "thousandth vernier" used in the works. The main scale of the gauge is graduated in fortieths of an inch. The enlarged illustration in Fig. 60 clearly shows the inches (on the main scale) divided into tenths and fortieths. Remember that $\frac{1}{40} = 0{\cdot}025$.

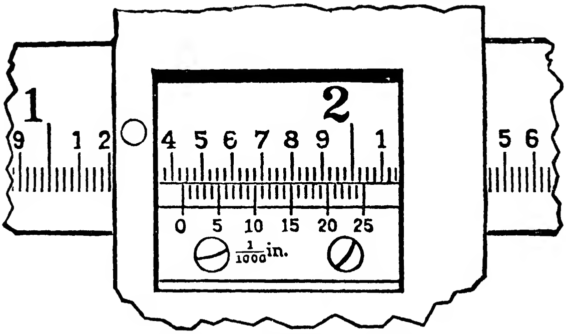


Fig. 60. A Thousandth Vernier

The vernier plate is $\frac{24}{40}$ in. in length. It is divided into 25 equal parts numbered 0, 5, 10, 15, 20, 25.

The difference between the width of one of the 25 spaces on the vernier and one of the spaces on the main scale is $\frac{1}{25} \times \frac{1}{40} = \frac{1}{1000}$ in. (0·001 in.).

Thus, if we set the vernier plate so that its 0 line coincides with the 0 line on the main scale, the next two lines will be 1/1 000 in. out of coincidence; the next two lines will be 2/1 000 in. apart, and so on.

To Read this Vernier (Fig. 60).

		In.
(*a*) Complete inches	1 . . .	= 1·0
(*b*) Complete tenths	4 × ·1 . .	= 0·4
(*c*) Complete fortieths	1 × ·025 .	= 0·025
(*d*) Note what line on the vernier scale coincides with a line on the main scale. Remember that each division on the scale = 1/1 000. In the illustration it is the eleventh line.	11 × ·001 .	= 0·011

Complete reading = 1·436

2. In which 20 divisions on the vernier or vernier scale equal 19 divisions on the main scale.

On the main scale the inches are divided into tenths and each tenth subdivided into five equal parts. Thus the whole inch is divided into fiftieths ($\frac{1}{50}$ = 0·02) of an inch.

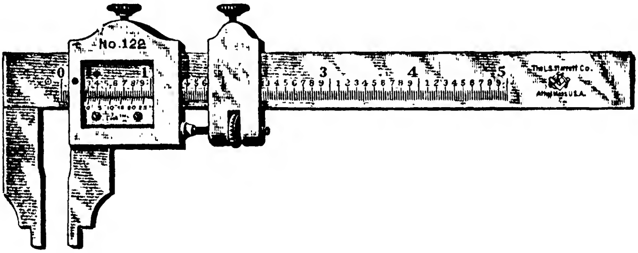


FIG. 61. A TYPICAL THOUSANDTH VERNIER CALIPER

On the vernier itself 20 divisions equal 19 divisions on the main scale. Thus, each vernier division being $\frac{1}{20}$ in. smaller than a main scale division, the vernier enables us to read to $\frac{1}{20} \times \frac{1}{50} = \frac{1}{1000}$ in.

This form of vernier caliper is not so common as that shown in Figs. 60 and 61.

To Read this Vernier. Note (*a*) how many inches, (*b*) tenths, (*c*) fiftieths the 0 mark on the vernier is from the 0 mark on the main scale. Then (*d*) note how many divisions (each counts 0·001 in.) there are from the 0 on the vernier scale to the line which coincides with one on the main scale.

The Ten-thousandths Micrometer (Fig. 62). Readings in ten-thousandths of an inch are obtained by means of the vernier consisting of ten divisions engraved on the sleeve as clearly shown in Fig. 62. These ten divisions occupy as much space as nine divisions on the thimble. Thus the difference between the width of one of the ten spaces on the sleeve and one of the nine spaces on the thimble is one-tenth of a space on the thimble.

How to Read the Ten-thousandths Micrometer (Fig. 62). First note the reading to the nearest thousandth as in the case of the thousandth micrometer previously explained. Then observe which line on the sleeve coincides with a line on the thimble. If it is the line marked 1, add one ten-thousandth (0·0001); if it is the line marked 2, add 0·0002, and so on.

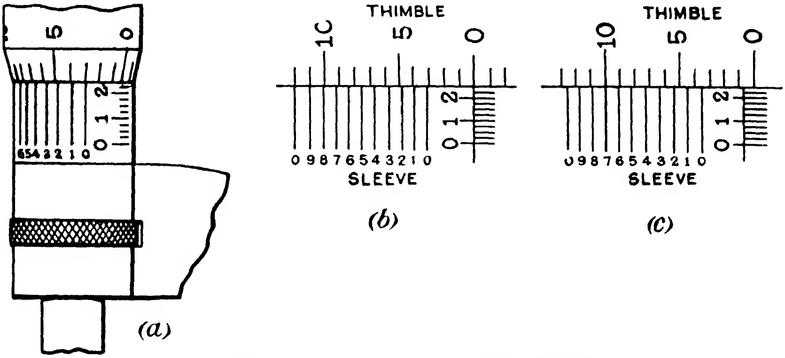


FIG. 62. TEN-THOUSANDTHS MICROMETER
Reading (*b*), 0·25 in.
Reading (*c*), 0·2507 in.

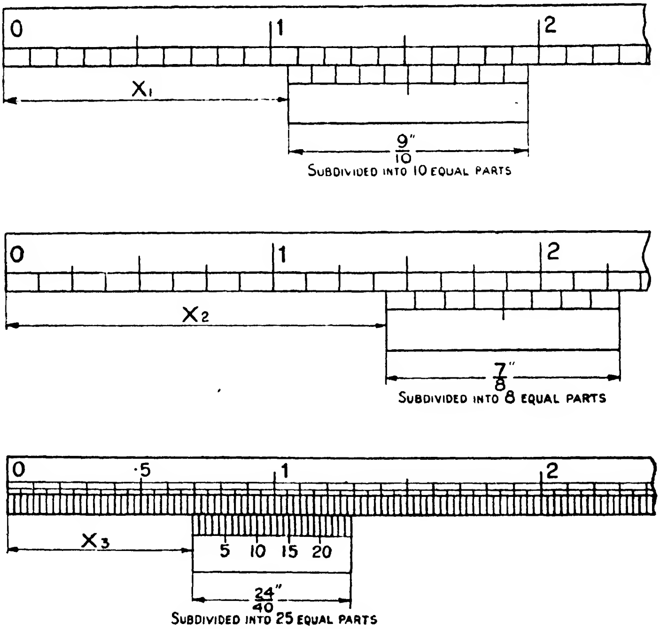

0
1
2
X₁
9"/10
SUBDIVIDED INTO 10 EQUAL PARTS
X₂
7"/8
SUBDIVIDED INTO 8 EQUAL PARTS
·5
X₃
5 10 15 20
24"/40
SUBDIVIDED INTO 25 EQUAL PARTS

FIG. 63
(See Exercise on page 75)

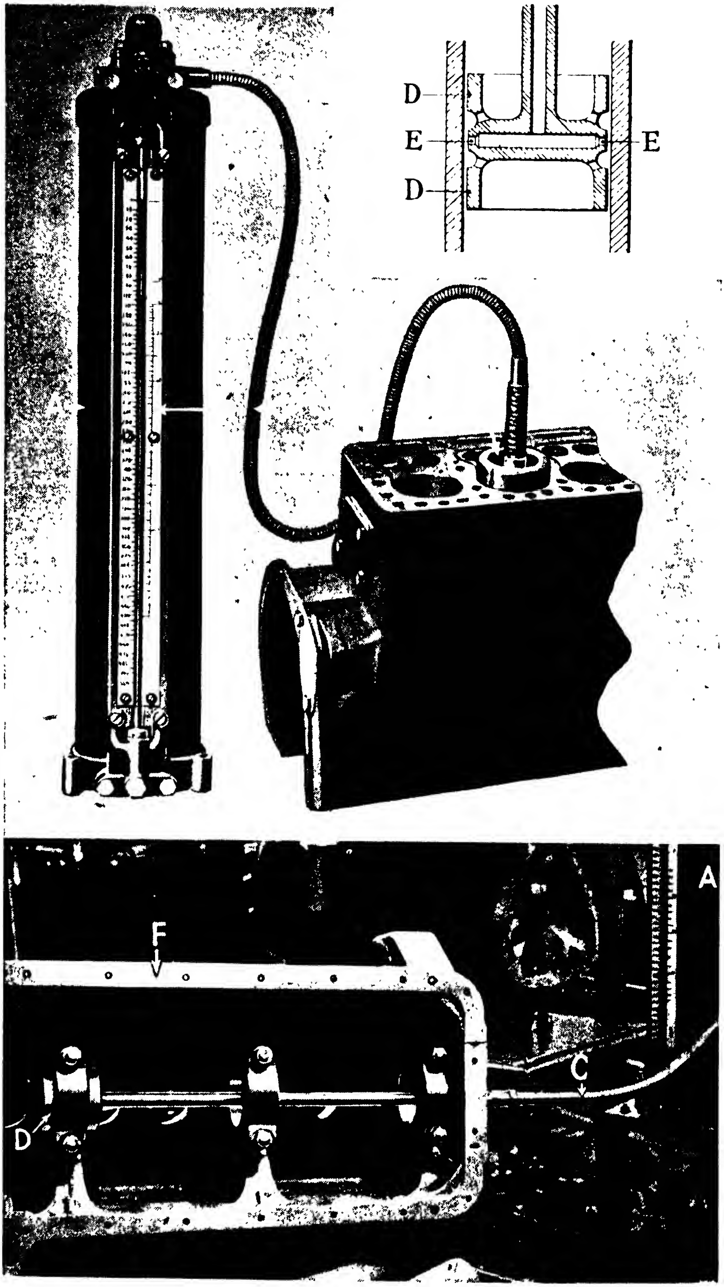


FIG. 64. SOLEX PNEUMATIC MICROMETER

A = Pressure controller
B = Graduated scale
C = Air pipe to gauge
D = Solex plug gauge
E = Air leak apertures
F = Crankcase and bearings

(*By courtesy of Messrs. Burton Griffiths & Co.*)

A Useful Exercise. Three combinations of plain and vernier scales are given in Fig. 63. Determine the distances X_1, X_2, X_3 by reading the respective combinations.

The Rule in General Terms—Applicable to Any Vernier. Let the length of the fixed scale that contains the same number of divisions as the vernier scale be a, and the number of these divisions be n. The vernier will be equal in length to $n - 1$ of these divisions. Since the distance a contains n equal parts, each division on the scale will $= \frac{a}{n}$. As the length of the vernier $= a - \frac{a}{n}$ and it is divided into n equal parts also, each division on the vernier is equal to—

$$\frac{a - \frac{a}{n}}{n} = \frac{1}{n}\left(a - \frac{a}{n}\right) = \frac{a}{n} - \frac{a}{n^2}$$

This shows that the difference between a division on the scale and one on the vernier $= \frac{a}{n^2}$.

For instance on some instruments the inches are divided into twentieths. The vernier is made equal to 24 of these and is divided into 25 equal parts. In this case the length a = 25 divisions of the fixed scale = 1·25 in.

As $n = 25$, we have,

$$\frac{a}{n^2} = \frac{1\cdot25}{625} = 0\cdot002 \text{ in.}$$

The instrument can therefore be read to $\frac{1}{500}$ in.

The Solex Pneumatic Micrometer (Fig. 64). This is used extensively in the aero and automobile industries for rapid checking of piston diameters, cylinder bores, etc. Essentially the apparatus consists of (1) a pressure controller for air supplied from the mains, (2) a column of liquid, with a scale, graduated either in metric or English units, on which dimensional variations of the part being measured are indicated, (3) a flexible pipe conveying air to the gauge, (4) the gauge.

The height of liquid is a measure of the pressure variation resulting from leakage of air between one or more nozzles incorporated in the gauge and the surface of the bore being measured. A typical male gauge is shown in the illustration. Note that there are two apertures directly opposite each other. The air leak and consequent pressure variation will occur in direct proportion to the clearance between the apertures and the bore. If the bore is exactly nominal size the reading will be zero. Thus the gauge can be used to explore the bore at any position for ovality; taper and plus or minus errors will be indicated by movement of the liquid column. On aero-engine work this micrometer can be used for the calibration of small apertures and flows, the measurement of bores of bearings, sealing capacity of valves, e.g. float chamber needle valves, etc.

"Feel" in Using a Micrometer. When using a micrometer, such as is shown in Fig. 55, the thimble is rotated until the anvil and the end of the spindle just touch the job being measured. This "touching" depends on the *feel* and the *sense of touch* of the operator. When using large micrometers a difference of half-a-thousandth may easily occur in readings taken by two different skilled persons on the same job.

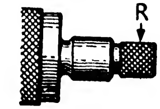


FIG. 64A

A device introduced to prevent undue pressure from being applied when rotating the thimble is the *ratchet stop* shown in Fig. 64A. When the small sleeve R is rotated it drives the thimble through a spring loaded ball engaging with teeth. Over-heavy "screwing up" is impossible, because the sleeve R is turned until the ball slips over the teeth. The pressure exerted by the anvil and the spindle on the work-piece is thus limited in its intensity. It is dependent on the loading of the spring in the ratchet stop and not on the *feel* of the operator.

To many skilled inspectors, however, ratchet stops generally seem somewhat fierce in action, and therefore they prefer to depend upon their own "feel" or capacity to rotate the screw with approximately equal torque every time. A skilled man sees that the micrometer screw is lubricated with a thin oil from time to time, and that the split nut is not too tight. A tight screw spoils the "feel." When using a micrometer of large size a heavy screwing action may cause the frame to spring open appreciably.

Inaccuracy of Micrometers. The micrometer may be termed an "end measuring" tool, the measurement being taken between the flat ends of two co-axial cylinders. The flat ends (anvil and spindle) are separated by means of a screw (generally 1/40-in. pitch). Common causes of error are thus: (1) measuring faces not flat, (2) measuring faces not parallel (or if parallel not square with axis of spindle), (3) zero error, (4) progressive error in screw.

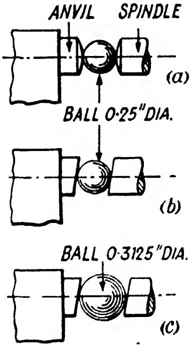


Fig. 64B

The flatness of the measuring faces can be checked by an optical flat. If pronounced convexity is present a ball of 0·25 in. dia. can be measured first in the centre of the faces and later at points near their outside edges. Any variations in the readings indicate that when the screw has been rotated ten times from zero the faces are untrue. (See Fig. 64B (*a*).) If only one ball were used and the end faces were flat but not square with the spindle axis the foregoing test might not reveal the error. Hence a $\frac{5}{16}$-in. ball could next be employed as this would require $12\frac{1}{2}$ turns from zero and the end faces would, if "out of parallel," interfere with the gauging of the ball in different positions. (See Fig. 64B (*c*.))

Zero error, if the end measuring faces are true and clean, is quickly corrected by adjustment, the method depending on the make of the micrometer. Before testing for zero error a piece of note-paper can be nipped very gently between the flat faces of anvil and spindle and pulled out gently against this pressure.

Progressive error in the screws of modern micrometers is usually very small indeed. There is little hope of detecting it if the measuring faces are out of truth. Granted that these faces are true the best test for progressive error is to set the micrometer to read thicknesses of slip or block gauges, increasing in size by multiples of 0·25, e.g. 0·25, 0·5, 0·75, 1 in. A good-class micrometer has a hardened steel screw (thread ground), and progressive error will probably not exceed 0·0001 in. over a length of 1 in. after long service in careful hands.

If the measuring faces are untrue they should be lapped square with the axis of the spindle and the anvil.

CHAPTER VIII

FURTHER PRECISION MEASURING APPARATUS

MEASURING MACHINES. The high degree of accuracy required in modern precision work calls for the measurement and checking of gauges, etc., with instruments of remarkable accuracy. Various types of very accurate measuring machines are made for use in tool-rooms and inspection departments. Most of them are supported on very substantial beds and embody essentially the characteristics of the first Whitworth measuring machine, i.e. an accurately cut screw of fine pitch, subdivided with a rotating graduated head, and having a gap between the end of the screw and the fixed abutment piece to receive the article to be measured. A number of firms make these highly accurate machines, e.g. Newall Engineering Co., Alfred Herbert Ltd., Pratt and Whitney, etc.

The production of an accurate screw as well as the mechanism of a divided head are less troublesome than the estimation of the degree of pressure between the measuring points and the work. It occurs, although not so obviously, in all calipers, hand and micrometric. It becomes necessary in many high-class measuring machine designs to provide means for indicating the exact degree of contact pressure which is admissible. A common device is a feeler plug that drops out between points when a certain pressure is reached, another is a spring-operated plunger working in unison with a scale and microscope, another is a graduated glass tube containing a coloured fluid, forced by the pressure of a diaphragm connected to the movable anvil, or a spirit level.

The Newall Measuring Machine (Figs. 65 and 66). This is carried on a substantial bed, the surfaces of which are scraped and lapped to ensure the alignment of the heads. The headstock gives readings to 1/100 000 in., the graduations being such that the indicated size can be read directly in decimals. The headstock for metric measurements gives readings to 1/10 000 mm. The measuring screw has a thread of deep buttress form to give ample wearing surface. It has a range of 1 in. or 20 mm. The measuring faces of the screw and nut are from two to three times as long as the travel of the screw so as to delay wear, and preserve the accuracy of the pitch.

The screw spindle runs in hardened steel bearings. An automatic adjustment maintains constant tension on the contact of the measuring screw between the effective faces of the screw and nut. Rapid movement of the screw is produced with a knurled nut at the end of the spindle, which is used until sufficient pressure has been applied through the piece being measured to bring an indicator into motion. A fine adjustment screw gives a sensitive movement to the measuring screw.

The pitch of the measuring screw is subdivided by the graduations round the measuring wheel seen at the right of Figs. 65 and 66, in combination with a scale and vernier, divided decimally.

Reading the Measurement (Fig. 67). The reading is 0·31254 in. and is obtained as follows—

The first digit, 3, is the highest figure disclosed on the left-hand side of the scale that carries the vernier. The second and third digits, 1 and 2, appear as the highest main graduations opposite the vernier. The fourth digit, 5, is the highest subdivision on the measuring wheel below the zero line on the vernier, and the fifth digit, 4, is the graduation on the vernier that coincides with any graduation on the measuring wheel. As the pitch of the measuring screw for

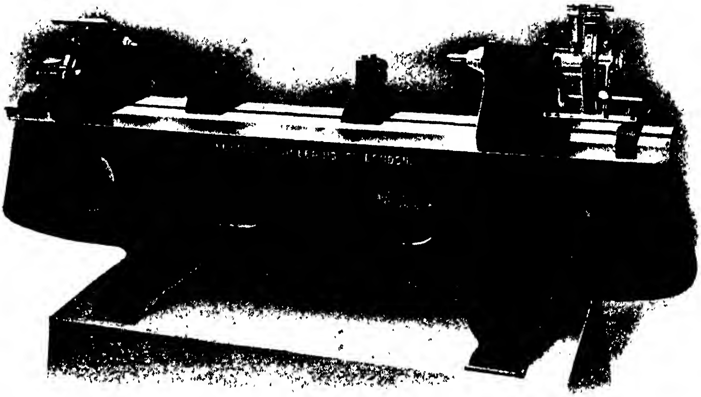


FIG. 65. NEWALL MEASURING MACHINE
(*By courtesy of Newall Engineering Co.*)

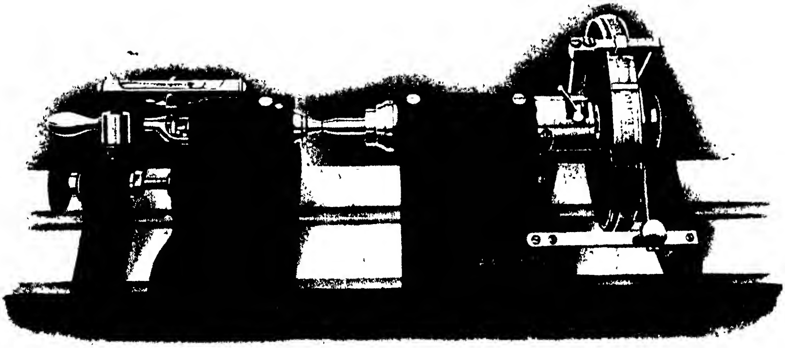


FIG. 66. NEWALL MEASURING MACHINE
(*By courtesy of Newall Engineering Co.*)

English dimensions is 20 threads per inch, it is necessary to add 0·05000 in. to the indicated size in all cases where the vernier may have passed the subdivision between any two main divisions on the scale that carries the vernier. Thus in Fig. 66, if the measuring wheel has been given one complete revolution outwards, the subdivision between digits 3 and 4 on the scale would be disclosed, and the reading would be: 0·31254 + 0·05000 = 0·36254 in.

The tailstock, seen at the left of figures 65 and 66, has an auxiliary saddle behind it, with a fine screw connexion to the tailstock to provide a very delicate movement for setting, either to zero, or to graduated lines on a rule. The **mechanism for setting and testing** is extremely delicate. For measurements up to 1 in. the anvil faces of headstock and tailstock are brought to about $\frac{1}{32}$ in. apart, with the reading on the vernier approximately zero. But for dimensions over 1 in. end measuring rods are supplied, or rules and a microscope. For lengths above 1 in. the length of measuring rod employed must be added to the reading obtained from the headstock. An indicator and a spirit level on the tailstock, Fig. 66, show the degree of pressure on the anvil by a movement of the bubble, which magnifies that of the anvil about 4 000 times. The possibility of varied readings by different operators is eliminated, and changes due to temperature are seen. The vee-rests seen in Fig. 65 support end measuring rods. The machine is used for measuring and checking gauges, to detect alterations due to wear, for duplicating standards, etc.

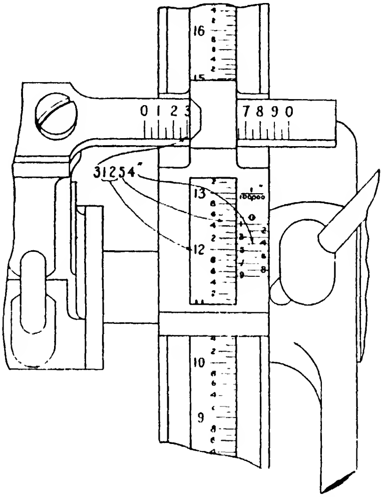


Fig. 67. Reading the Measurement

P.V.E. Diameter-measuring Machines. These machines, made by the Pitter Gauge and Precision Tool Co. Ltd., are designed to measure the diameters of screws or plain cylindrical plug gauges, or other work where accurate determination of size is required. (See Fig. 68.)

The effective and core diameters of screw plug gauges are measured on the machine by means of effective diameter measuring rods and core prisms. The rods and prisms are suspended from supports fixed on the top or floating carriage so that they may be applied to the screw in a manner shown opposite.

When it is desired to use the machine as a comparator it is then necessary to calibrate by means of slip gauges or preferably reference discs of approximately the size of the work to be tested. By this method it is possible to estimate readings on the micrometer to ± 0·000025 in.

The machine consists of a base, intermediate slide, and a top slide or carriage.

The base is a casting with brackets for the work-holding centres and two vee-grooves (one long and the other short) are ground in the upper part of the base.

The intermediate slide is a flat casting with two cone studs on the under-side. These cones, one fixed and the other adjustable, fit in the long vee-groove on the base casting and a steel roller is placed in the short vee-groove and also between the retaining pins on the under-side of the intermediate slide. On the upper side of this slide are ground two vee-grooves.

The top carriage is a casting with two brackets, one being provided for the micrometer and the other for the mechanical indicator. The carriage is mounted on three steel balls, two in one vee-groove in the intermediate slide and one in the other vee-groove, the balls being retained by pins in the top carriage. Thus the intermediate slide is capable of longitudinal movement and the top carriage transverse movement.

The micrometer is of special design and is provided with a large Duralumin drum graduated in 0·0001 in.

The mechanical indicator is designed and certified by the National Physical Laboratory. The purpose of the indicator is to provide a movable anvil, the displacements of which are magnified with reference to a fiducial line and further to provide a means for operators to obtain repetitive results. The magnification of the displacement of the anvil is obtained by a two-stage system of levers giving a ratio of approximately 250 to 1 and which gives 0·025 in. movement of the point of the needle for a movement of 0·0001 in. of the anvil. (The foregoing descriptive notes were supplied by the makers.)

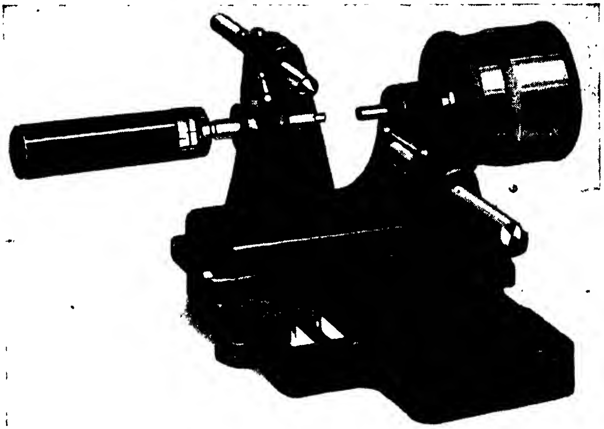


FIG. 68. P.V.E. DIAMETER-MEASURING MACHINE

Fig. 105. This shows a close-up view of the measurement of a screw plug gauge. The effective diameter is being measured by means of a P.V.E. measuring machine and thread measuring wires or cylinders.

THE USE OF PRECISION BLOCKS AND SLIP GAUGES.* The use of precision blocks and slips enables the making up, or checking, of a dimension by combining together a number of blocks, perfectly parallel, of definite thickness, and made within very fine limits. They eliminate the errors of the human element, in consequence of which different men obtain various results from calipers and rule, and even from micrometers, and they do not require such frequent inspection and correction as is necessary with micrometers, consequent on wear and rough usage. The best-known precision blocks are possibly

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* B.S.S. No. 888—1940 is concerned with Slip (or Block) Gauges of three grades. An appendix gives useful information on their care and use.

those made by the Swedish C. E. Johansson Co. Ltd., Coventry. Mention should also be made, however, of the very similar "Matrix" gauges marketed by the Coventry Gauge and Tool Co. Ltd., those made by the Pitter Gauge and Precision Co. Ltd., and other firms. They are not of the same type as the reference blocks described in connexion with the Newall system, in which a single block has one dimension, or two, and is not related to any other. The Johansson blocks give sizes advancing by very minute increments, expressed in decimals, by the selection and addition of which many thousands of combined dimensions can be obtained. It is a remarkable fact that cumulative errors are unknown, for however numerous the blocks selected they give the total correctly if tested with a gauge. The blocks are therefore self-checking. Their uses include checking the accuracy of snap gauges and internal limit gauges; re-setting adjustable gauges to new limits and correcting them for wear; setting heights for sine bars; measuring dies, jigs, etc., and for general inspection. The blocks are made in sets of standard measures, and for limits, in English and metric units. *They are made in four qualities or degrees of accuracy,* two for standard use or reference, and two for shop services. The highest tolerance in the first is 0·000002 in. per inch, and in the lowest is 0·000012 in. per inch. In

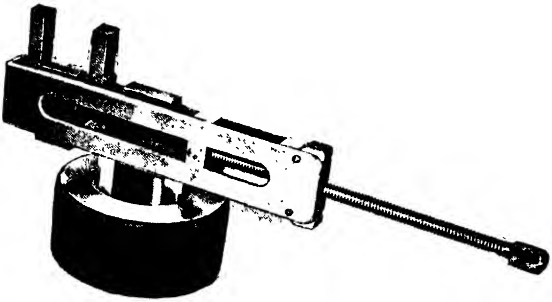


FIG. 69. BLOCKS AND SLIPS CONVENIENTLY SECURED IN A HOLDER

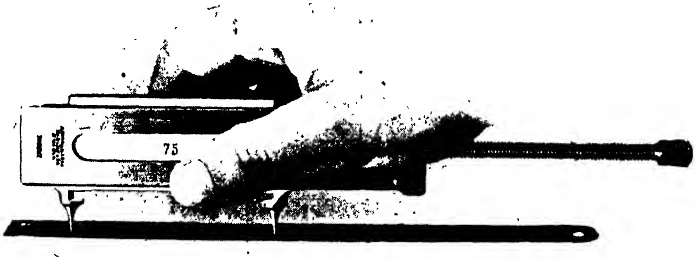


FIG. 70. POINTS SET BY BLOCKS SECURED IN A HOLDER

metric measures the highest is 0·00005 mm. per 25 mm., and the lowest is 0·0003 mm. per 25 mm. The B.S.I. recommend three grades of accuracy.

Building-up Dimensions. Johansson blocks for general or standard use are made in two sets in English sizes and in five sets in metric sizes. With these sets dimensions can be built up from 0·1 in. or from 1 mm. to the combined length of all the blocks placed face to face. The difference between the sets consists in the number of blocks. In the larger sets it is possible to build up the desired dimensions with a minimum number of blocks. From the smaller sets a larger number of blocks must be used to build up the same dimension. The largest standard set contains eighty-one blocks in four series. Nine in the first series range from 0·1001 to 0·1009 in., forty-nine in the second series range from 0·101 to 0·149 in., nineteen in the third series from 0·050 to 0·950 in., and four in the fourth series from 1 to 4 in. And these are supplied in three degrees of accuracy. The blocks in the first series will divide up the spaces between those of the second series, and those of the third and fourth series can be divided up by the first and second series. Over 80 000 different sizes can be obtained, accurate at 68° F. The dimension required is most readily obtained by eliminating the smallest decimal, working from right to left, and finishing with the largest block.

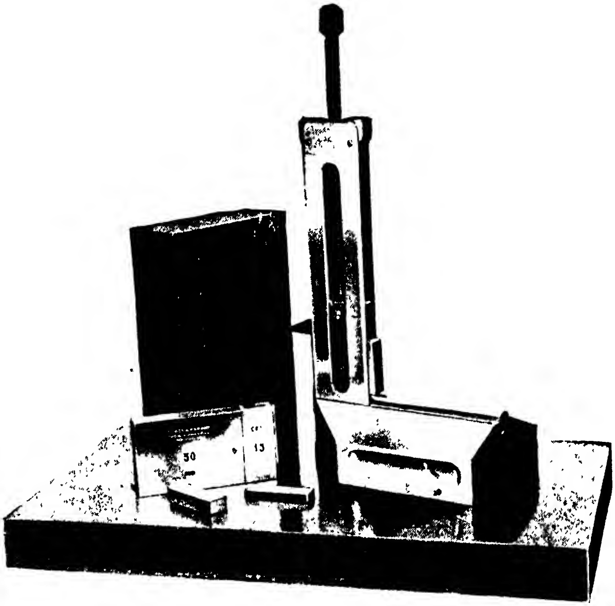


FIG. 71. SCRIBER POINT SET BY MEANS OF BLOCKS AND SLIPS SECURED IN A HOLDER

Thus, required—

1·248 in.	2·6483 in.	0·8391 in.
0·148 ,,	0·1003 ,,	0·1001 ,,
0·100 ,,	0·1480 ,,	0·1090 ,,
1·000 ,,	0·4000 ,,	0·1300 ,,
	2·0000 ,,	0·5000 ,,
1·248 ,,		
	2·6483 ,,	0·8391 ,,

The limit gauge blocks, made also in English and metric measures, contain eighteen blocks, in two series, nine having minus or negative dimensions, and nine plus or positive sizes. In one set of eighteen, the + and − blocks have a range of 0·0001 to 0·0009 in.; in the other set the range is + and − from 0·001 to 0·009.

Thus, required—

4 − 0·005 in.	6 + 0·0065 in.
0·1 − 0·005 ,,	0·1 + 0·0005 ,,
0·9 ,,	0·1 + 0·006 ,,
3 ,,	0·8 ,,
	5 ,,
4 − 0·005 ,,	6 + 0·0065 ,,

There are several accessories by the use of which the usefulness of the blocks can be extended. A set of large blocks is made up to 20 in., by which the range of the fractional blocks is much extended. Holders are provided for the blocks by means of which jaws are set for gauging external surfaces, and for bores. (See Fig. 69.) Points are set for checking graduations. (See Fig. 70.) Jaws and points may be wrung on to the slips, but it is generally more convenient to fix them in a holder. Scriber points are set from a base block. (See Fig. 71.) Adjustable snap gauges are set with the blocks. (See Fig. 72.)

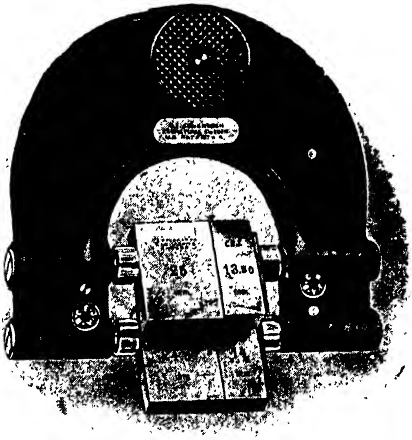


Fig. 72. Using Blocks and Slips to Set a Limit Snap Gauge

A remarkable feature of the best slip gauges is that when the surfaces are wiped, and the blocks slid over one another to expel air, they adhere like magnetized steel. Though turned about in any positions they will not separate. The surfaces are highly finished like burnished silver, and the thicknesses are so perfectly parallel that turning about the blocks end for end does not affect the accuracy of the combination. Blocks should be separated by sliding them apart and not by direct pulling or forcing one away from the other. Naturally they must be used and preserved with the greatest care. In Fig. 73 is shown a set of Matrix slip gauges made by the Coventry Gauge and Tool Co. Ltd.

Degrees of Accuracy. Considering that normal working limits on production-pieces are in the region of ten-thousandths of an inch it may be wondered whether there is any good purpose in aiming at a gauge block accuracy of "a millionth." Perhaps it will prove interesting to mention some remarks made by Mr. J. E. Sears during the course of a lecture to the Institution of Mechanical Engineers. Three-inch shells were produced during the war of 1914–18 with a 0·01 in. tolerance on the diameter. Checking of this dimension was made with two ring or snap gauges differing in nominal size by 0·01 in. Of course a gauge cannot be made exactly correct, so that the gauge maker must be allowed a tolerance. The latter must of course be finer than that allowed on the shell, otherwise the shell maker would be penalized unduly on the one hand, or parts might be passed by the gauges which were well outside the nominal limits. Therefore in this case the gauge maker was allotted a tolerance of 0·005 in. The gauges were next tested with combinations of slip gauges and it was stipulated that each of these combinations, comprising several blocks, was to be accurate to within 0·00001 in. (or 1 part in 100 000 on the larger sizes). From this it follows that yet finer measurements had to be taken in the standardizing laboratory where the blocks were checked. As the tolerance for these was only 0·00001 the laboratory had to be able to take measurements to an accuracy of 0·000001 in. Fine measurements are ultimately necessary, therefore, even when planning the inspection of work to comparatively coarse limits.

FIG. 73. MATRIX SLIP GAUGES

CYLINDRICAL END-MEASURING BARS. These extend the usefulness of sets of slip gauges, the rods usually being cylindrical, of about $\frac{7}{8}$ in. dia., and having end faces which are flat and parallel within close limits.

When used horizontally the longer rods have to be supported with great care because they bend or sag under their own weight and thus throw the ends "out of parallel." If a bar has uniform section the distance of these supporting points from the ends is 0·211 times the length of the bar. These supporting points are known as "Airy" points. Some standard length gauges are provided with narrow collars at the "Airy" points. The Pitter Gauge and Precision Tool Co. Ltd., and the Coventry Gauge and Tool Co. Ltd. guarantee their standard reference bars to the following limits—

End faces flat within 0·000005 in. (0·0001 mm.).

End faces parallel within 0·00001 in. (0·0003 mm.).

Length between measuring faces accurate within 2½ parts in a million at standard temperature.

Various fittings can be attached to the bars so as to convert them for use as height and caliper gauges of great accuracy. Thus in Fig. 74 one end of a bar is held in a base whilst a collet is slipped over the other end to secure a jaw. To get the exact setting required slip gauges can be added between the collet and the jaw. Fig. 74 shows a P.V.E. Workshop Bar taking an accurate height measurement on a jig. Cases of P.V.E. workshop bars and slip gauges are also shown.

Standard bars are similar to workshop bars but, as their name implies, are used for reference purposes on highest grade work and for checking combination workshop bars or other secondary standards. The P.V.E. standard bars are made by the Pitter Gauge and Precision Tool Co. Ltd. to a high order of accuracy, viz. 2½ parts in a million, but for special purposes they can be made to an accuracy of 1 part in a million.

COMPARATORS. Micrometers, verniers and similar workshop measuring tools suffice for a great many purposes. When really high-grade work (especially tools for producing high-grade work) is being inspected, singly or in quantities, there is need for more precise measurement. It is here that the *comparator* proves its usefulness.

Probably it will now be best if the reader studies the notes describing the *Matrix Level Comparator*. Speaking generally, comparators are used to check the dimensions of a work-piece by first setting the gauge to read zero when a plunger rests on block gauges or end measuring bars of the correct height or dimension. When the block gauges have been removed the work-piece can be placed on the table beneath the plunger. On some comparators a needle then shows the difference between the dimensions of the gauge and the work-piece. When the instrument is used in this way, therefore, it cannot be described as a means of *direct* measurement. It enables a *comparison* to be made between the dimensions of a work-piece and of standard gauges (e.g. blocks or slips). In the **Zeiss Orthotest Comparator** the movement of the plunger is communicated to a needle by means of a multiplying mechanism. The point of the needle moves across a graduated dial marked in ten-thousandths of an inch. The **Zeiss Optimeter** is another well-known comparator but in this design the multiplication of movement of the plunger is carried out by optical instead of mechanical means. In the "Level" comparator a sensitive spirit level is used as an indicator. The **Prestwich Fluid Gauge** is a comparator which uses a hydraulic method of multiplication.

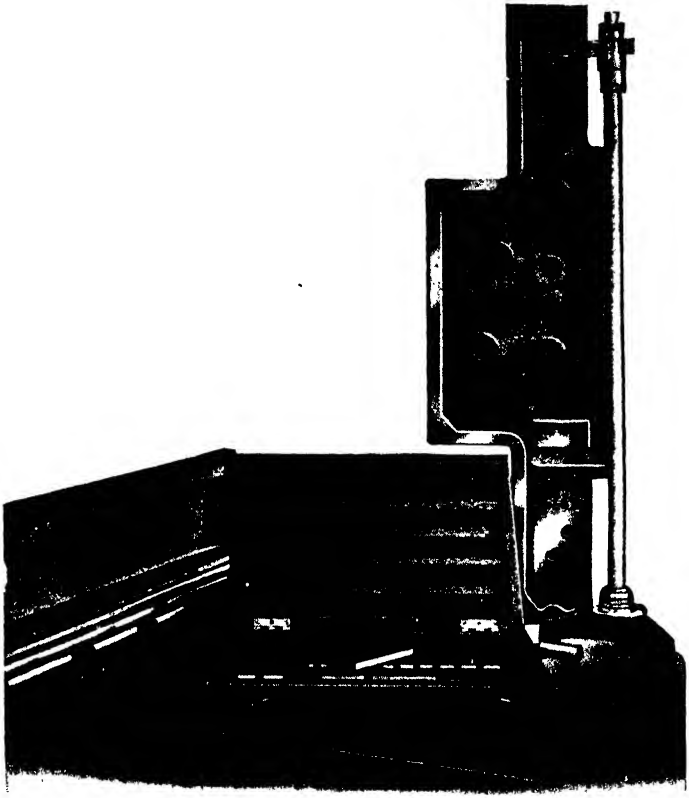


FIG. 74. ACCURATE MEASUREMENT OF A JIG BY MEANS OF A P.V.E. WORKSHOP BAR

The keystone of size control is the comparator, for without one, calibration—or reference—standards are of little use. It is the only means of checking standards within themselves, and inspection- and workshop-slip gauges and bars against standards. The P.V.E.

Generator Comparator is well known. The Pitter Gauge and Precision Tool Co. Ltd. also market *The Eden Millionth Comparator* which is of N.P.L. design and enables comparisons of slip gauges to be made very easily. We shall now describe the *Matrix Level Comparator* made by the Coventry Gauge and Tool Co. Ltd. (See Fig. 75.)

Description. The Matrix Level Comparator is of a type originally developed by the National Physical Laboratory. It enables differences in length up to 0·0001 in. to be measured to within one millionth of an inch *by simultaneous comparison* with end measuring rods or slip gauges of known size. Differences of more than 0·0001 in. must be made up by means of suitable slip gauges of known size.

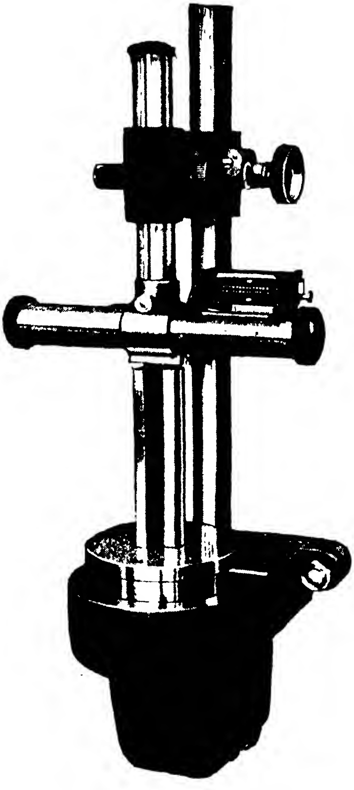


Fig. 75. The Matrix Level Comparator

(By courtesy Coventry Gauge and Tool Co. Ltd.)

Principle. A hard steel disc of approximately 5 in. diameter with surfaces flat and parallel to the order of a few millionths of an inch is free to be rotated on the substantial bracket of the instrument in an approximately horizontal plane. The known standard together with the gauges to be measured are placed side by side on the platen.

Above the free ends of these gauges is suspended a highly sensitive level. The level tube is carried in an aluminium cradle, on the under-side of which are attached a pair of steel balls. When making comparisons, the two balls must bridge the two gauges. The position of the end of the bubble is then read off the scale, the level raised for a moment while the platen carrying the gauges is rotated through 180° and the level lowered again and a second reading taken. One half of the difference between the readings obtained is equal to the difference in length between the gauges.

Operation. The bubble tube fits lightly in the aluminium cradle and a scratch on the glass indicates the position in which the weight of the tube balances over the ball contacts. Having set the bubble tube in the correct position endwise, the tube itself should be rotated until the arrow marked on the glass is exactly in the centre of the air bubble. The length of the air bubble should be about the same as the length of the aluminium cradle. The bubble tube has a chamber at one end and by tilting the tube on end, more or less air is trapped in this chamber, thereby lengthening or shortening the bubble.

Gauges are usually wrung to the platen, but with large gauges such as 12 in. lengths, this may be dispensed with and the gauges floated on a few drops of paraffin oil. In order to wring gauges successfully they must be free from burrs and have a good finish. It is advisable to have a hard Arkansas stone and a cast-iron lapping plate at hand to remove any burrs. For the production of wringing films, special fine cotton wipers or chamois leather are recommended.

It is obvious that gauges must equalize in temperature before comparisons are made. While pieces below say 0·2 in. will equalize immediately when wrung to the platen, time must be allowed for larger sizes. The actual time required will also depend on the difference of temperature prior to wringing to the platen, but generally speaking 4 in. gauges require about thirty minutes before comparisons of say 5 millionths of an inch can be definite. Gauges will equalize a little sooner after mounting if the free ends are bridged by means of a polished plate such as a discarded 2 in. slip gauge. This plate is placed on top of the gauges and removed when making comparisons. Readings may be taken from time to time to see how equalizing is progressing.

When the gauges have equalized, the level is carefully lowered by means of the knob until the balls are just touching the ends of the gauges. Contact should be made in such a way that no sound is made. After this, the housing should be lowered a little farther to ensure that the level is completely free and rests only on the gauges to be compared. The free movement inside the housing is about $\frac{1}{16}$ in. so that after contact has been made, the level may be lowered a further $\frac{1}{32}$ in.

Readings are taken by observing the extreme end of the air bubble. This is done by looking horizontally into the mirror. The end of the bubble will appear in the centre while the scale is observed on either side of the mirror.

To take an example—

If the first reading is 10 and the second 15, on an English scale, the difference in length is—

$$\frac{15-10}{2} = 0{\cdot}000025 \text{ (25 millionths of an inch)}$$

As mentioned previously the comparator is sensitive for measurements of 1 millionth of an inch, but with special care this can be improved on to 5 ten-millionths of an inch. When making comparisons to this order, however, it is essential to adjust the bubble so that there is very little movement of same between the readings taken. Adjustment is effected by means of the small screw near the contact balls. (The foregoing descriptive notes were supplied by the makers.)

A typical example of the use of slips is shown in Fig. 76 (reproduced by courtesy of the Coats Machine Tool Co. Ltd., London), where a Prestwich Fluid Gauge is shown.

The machine used as shown may be termed a comparator, the slips enabling it to be set to 0·8785 in. for measuring pneumatic hammer valves of the type shown. In building up the slips it is a good plan to work backwards, eliminating the fourth decimal figure, i.e. select 0·1005 in. first, leaving 0·778 in. The next block will be 0·108 in., leaving, after subtraction, a balance of 0·670 in. The blocks 0·170 in. and 0·500 in. make the desired total. An alternative method of building up the dimension would be 0·1005 in. + 0·1280 + 0·6500 in. (depending on make of slips available and their number).

THE ELECTROLIMIT GAUGE. In essence this is a comparator depending for its action on mechanical gauging contact and electrical magnification of movement. The gauges are set by known standards, and the displacement of the gauging point, caused by variation in the size of the work being inspected, controls an electrical circuit in such a way that errors are shown in a greatly magnified, and therefore easily visible, form on the dial of a microammeter.

The Electrolimit Gauge principle is capable of wide application, and has been adapted to the production of comparators for external and internal measurements, continuous gauging of strip materials, and measuring the thickness of plating layers. We shall now describe some **Taylor-Hobson Electrolimit Gauges.**

In all its forms the Electrolimit gauge consists of four main units: the electric head with mechanism for contacting the work, the power unit, the indicating microammeter, and the stand which supports the electric head and carries an anvil in its base.

The working principle is that of a balanced A.C. bridge of four inductance coils. Two of these coils are built into the electric head and have between them a steel armature coupled to the gauging spindle. The bridge circuit is balanced to give zero meter reading when the armature lies mid-way between the coils in the electric head; a displacement of the armature, due to the movement of the gauging spindle, alters the balance of the bridge circuit. This causes current to flow through the microammeter, the amount of which is in proportion to the displacement of the armature. The sensitivity of the circuit is governed by the separation of the coils from the armature. Hence, when the coils are adjusted so as to be close to the armature the magnification is high; as the coils are separated from the armature the magnification decreases. The adjustment is described below.

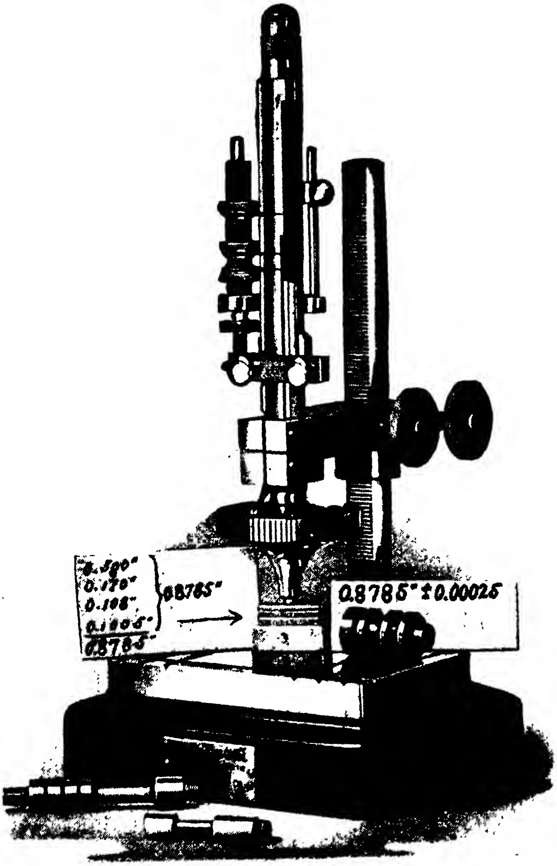


Fig. 76. Prestwich Fluid Gauge

(i) **External Master Gauge.** Fig. 76a illustrates the Electric Head of the External Electrolimit Gauge, and clearly shows the armature, hinged at one end, lying between the two inductance coils T_1 and T_2. Adjusting screws can be seen for altering the separation of these coils from the armature. The gauging spindle (S), the lower end of which is tipped with either a diamond or tungsten carbide insert, makes contact with the work, and movements of this spindle are communicated to the armature. Displacements of the armature are electrically amplified and indicated on the microammeter scale.

Fig. 76B shows the **External Electrolimit Gauge,** the principal components of which can easily be recognised. In addition to the adjustment provided by screws, provision is made for fine adjustment of the magnification by electrical means, using a knob in the base of the gauge. Coarse and fine adjustments for the zero setting are also provided in the electric head and gauge base respectively. Magnification is adjusted in accordance with the tolerance allowed on the work being inspected. This is set, as a rule, by means of standard slip gauges. The method adopted is to choose three slips (for maximum, zero, and minimum) of which the maximum difference is to represent the proposed full-scale reading of the meter and place them, side by side, on the gauge anvil. With the intermediate (zero) block under the gauging spindle, the gauge head is raised or lowered sufficiently to bring the pointer on to the zero mark and set exactly by means of the zero adjustments; the other two slips are then placed in turn on the anvil under the gauging point and the positions of the coils progressively adjusted (either towards or away from the armature) until the magnification is such that the larger slip gives the maximum scale reading while the smaller block gives the minimum reading. An alternative method of making the magnification setting would be to take three work pieces representing the maximum and minimum tolerable sizes and the correct (zero) size and to use these instead of gauge blocks.

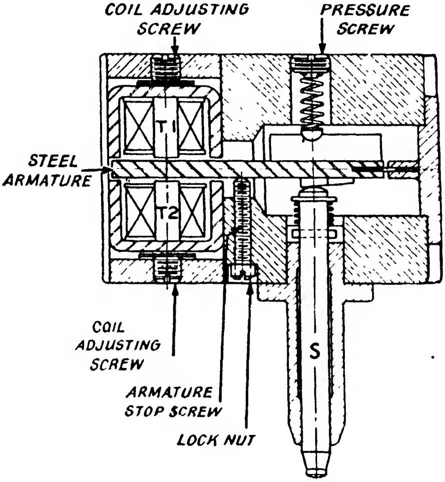


FIG. 76A. HEAD OF ELECTROLIMIT GAUGE

The Microammeter usually has a scale length of $3\frac{1}{4}$ in. By varying the magnification, this can be made equivalent to a displacement of the gauging point ranging from 0·00025 in. to 0·004 in. Thus, at the highest magnification, where 0·00025 in. is magnified to a pointer movement of $3\frac{1}{4}$ in. a scale division of such easily visible size as $\frac{1}{16}$ in. will be equivalent to approximately 0·000005 in. Set to its least sensitive condition, the same size scale division would be equivalent to 0·00008 in.

The Electrolimit Gauge finds extensive use in every branch of engineering in which high precision and close tolerances are of prime importance. In the production inspection of a wide variety of work, it can be operated without any attention over long periods. The magnification can be adjusted to suit the tolerances on the work inspected, and hence inspection is made easier and correspondingly more rapid. The provision for variable magnification makes this gauge extremely valuable for Standards Room applications.

Cylindrical Type Gauging Head. A gauging head of a cylindrical type is also available. It was designed with the object of being used in the 28 mm. diameter cylindrical holders which are already in use in many production units. This type of gauge employs a considerably modified and improved electrical circuit giving great freedom from variation due to voltage fluctuations. It is intended mainly for comparatively low and fixed magnifications, but is also provided with a variable control permitting of three magnifications. This head is so designed that it can be applied during grinding or machining operations, and for this purpose is sealed against the entry of cutting lubrications, etc.

(ii) **Internal Gauge.** A variation of the Electrolimit Gauge is the model for measuring internal diameters and is illustrated in Fig. 76c. The Internal Gauge utilises a spindle to act as a plug member for the hole to be measured. A pressure shoe arrangement pulls the work on to a pair of tungsten carbide inserts, the edges of which are formed into a suitable radius proportionate to the diameter of the hole to be gauged, thus forming two lines of contact between the work and the spindle. The diamond gauging point makes contact with the work opposite the T-C strips and the whole assembly forms a three-point gauging system.

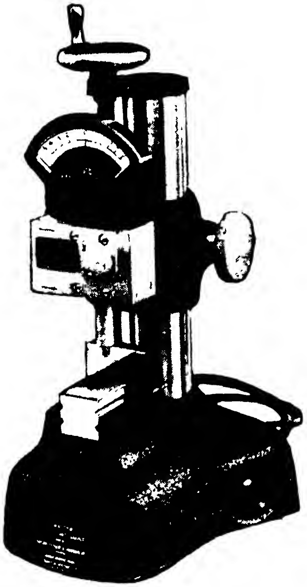


Fig. 76b. External Gauge

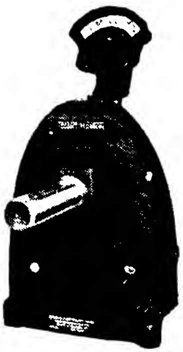


Fig. 76c. Internal Gauge

Turning the work on the spindle enables lack of roundness to be detected and measured, whilst moving the work backwards and forwards along the spindle shows up lack of constancy in the diameter of the hole. By means of suitable spindles, holes upwards of ½-in. diameter can be measured. The gauge is made in two main models. Fig. 76c shows the bench-form gauge in which the work is offered to the gauge; this is suitable for light, easily handled parts. For gauging heavier work the plug element must be presented to the work, and, for this purpose, special hand units have been developed which embody the plug and also the electric head. The indicating meter and power unit are suitably placed whilst the hand unit is connected to them by means of a flexible cable. A special model is available for inspecting the bore of cylinders of internal combustion engines, and there is also a model suitable for the inspection of gun-bores. Special models are available for measuring small bores for fuel injection pumps calling for close limits of accuracy.

The internal gauges must be adjusted by means of suitable master ring gauges; their magnification can be altered in a manner similar to the External model, but they are meant essentially for production inspection, since a special plug element is required for every hole to be gauged. They are ideal for the inspection of mass-produced work which must be held to close limits and enable components to be graded for selective assembly. Successful applications have been found to many gauging problems notably in the manufacture of aeroplane engines, for example, in the measurement of cylinder bores, connecting-rod bearings and gudgeon pin holes in pistons.

(iii) **Continuous Gauges.** A special type of Electrolimit Gauge has been developed for measuring continuously the thickness of strip materials as they travel through the Rolling Mills. This is in general use on Steel, and Aluminium Rolling Mills. The measuring unit is arranged on a slide so that it can travel across the strip in order to measure the thickness at any point on its width. Obviously the design of the measuring device must be robust enough to withstand the heavy vibration and rough handling to which it is subject. These gauges stand up to a hot, steam-saturated atmosphere, and work efficiently without attention even under a stream of water.

The moving strip from the mill passes between a pair of spring-loaded contact rollers, one of which is linked to the armature in the electric head of an Electrolimit Gauge. Variations, in the separations of the rollers, due to changes in thickness of the strip between the rollers, are electrically magnified in a manner similar to the Internal and External Gauges. The indicating meter is placed in some position where it can readily be kept under observation by the mill operator. In addition, a recording device can be made to trace on a paper a continuous record of any variations in thickness of the sheet during the running of the mill.

(iv) **Plating Thickness Gauge.** It is frequently necessary to measure the thickness of a coating or plating on iron or steel. A special form of Electrolimit Thickness Gauge can be used for this purpose when the plating is non-ferromagnetic, e.g. chromium or copper, and is deposited on a magnetic base, such as ron or steel. In the normal course of events it would be necessary to damage or even destroy the sample in the course of measuring the thickness of the coating. The specimen has also to be prepared and the making of each individual measurement occupies some time.

When using the Electrolimit Thickness Gauge, it is only necessary to place the hand unit in contact with the sample wherever the thickness of the coating has to be measured and an instantaneous reading is obtained. As many readings can be taken as desired just as quickly as the hand unit can be placed in the required position, hence the entire surface can be explored and variations in thickness of the coating measured.

Before use, the zero reading of the meter is adjusted with the hand unit in direct contact with a piece of steel. When placed on plated work, the separation between the unit and the iron or steel base, due to the interposed plating, has the same effect as the movement of the armature when using other forms of the Electrolimit Gauge. The meter is calibrated in terms of this separation, and thus gives a direct reading of the plating thickness.

Horizontal Comparators. Whilst most comparators are of the vertical type, the *horizontal comparator*, a typical example of which is the *Cooke Horizontal Comparator* marketed by Cooke, Troughton & Sims, Ltd., has a wide sphere of usefulness, being particularly useful in the verification of diameter, roundness and parallelism of plug and ring gauges, and of pitch diameter in both male and female screw gauges.

Measurements by means of the Cooke Horizontal Comparator are made in the horizontal plane between a fixed point and one whose movement is indicated by the *opticator*, which is designed to make a minute measurement, and to magnify the result to an extent whereby the eye can appreciate it comfortably. The plunger which makes contact with the work controls the movement of a mirror. Light from the illuminating unit is passed through a scale engraved on glass from which it reaches the mirror, whence it is returned to a translucent screen contained within a hood, a magnified image of the scale being formed on the screen.

The total magnification of the movement of the plunger registered on the screen is approximately 1000×. That is to say, a movement of the plunger of 0·001 in. will translate the image of the scale across the screen by 1·0 in. There are 20 divisions contained within 1·0 in. on the screen, thus one division of the projected image of the scale corresponds to 0·00005 in. movement of the plunger. It is convenient to estimate readings to one-fifth of a division which is one hundred thousandth part of an inch. The overall length of the scale image represents a movement of the plunger of 0·01 in. or ± 0·005 in.

In all indicating instruments designed to show magnifications of movements the practical difficulty to be overcome is the friction inherent in the mechanical elements of the magnifying system. The *opticator* has one moving element, namely, the plunger which contacts with the work and the mirror associated with it. The remainder of the system is entirely optical, and is therefore unaffected by friction, etc.

Standard Gauging Temperature. The amount by which a 1-in. length of a material increases with 1° C. rise in temperature is called the *coefficient of linear expansion*. It is shown in books on Heat that superficial expansion is approximately twice as much as linear expansion, and that cubical expansion is approximately three times as much. Values of the linear coefficient are different for all the common engineering materials. Typical values for range 20/600° C.: Pure iron, 0·0000147; mild steel (0·25% C.), 0·0000143; aluminium, 0·000027; copper, 0·0000187. Clearly, then, it is of little use to discuss accuracy in terms of a millionth of an inch unless we note that whilst all metals increase in length as temperature rises, the *rate* of expansion depends on the material. A gauge might increase by some 200 millionths of an inch for a 30° F. rise in temperature. To secure some uniformity in respect of these matters gauges and reference standards are made to correct sizes at a standard temperature of 68° F. (or 20° C.). This is also the temperature at which fine precision measurements and comparisons are made, care thus being taken to avoid differences in temperature between the gauge and the work. The only error that can normally arise by measuring at a temperature of 68° F. is due to difference between rates of expansion of the gauge and the work. When measuring bronze or aluminium with steel gauges the effect of working at a temperature other than 68° may be serious. The handles of master gauges, etc., are often covered with an insulating material to guard against heat gains due to contact with an inspector's hands.

OPTICAL MEASURING

1. Toolmakers' Microscopes. Optical methods of inspecting, comparing, and measuring tools, jigs, templets, and finished parts have been used in modern shops and inspection rooms for some years and the number of applications of this procedure is steadily increasing. Until fairly recent times optical apparatus, e.g. microscopes and magnifiers, was designed for laboratory rather than workshop use. Nowadays, however, a range of sturdy "toolmakers' microscopes" has become available, of which we may take the well-known Bausch & Lomb Optical Co. Ltd. products as typical. See Fig. 77, where is shown a Bausch & Lomb toolmaker's microscope. This gives an enlarged image and shows objects in their natural aspect and direction—not reversed as in the ordinary laboratory microscope.

In use the inspector places the work to be examined on the cross-slide stage and clamps it in position. He then focuses the microscope on the work, and brings the part to be measured directly under a cross-line, which is seen in the microscope tube. The cross-line is an index both practical and precise. In this microscope the image appears right side up, the movements to the right appear in the microscope to move to the right.

The cross-slide stage or table is controlled by two micrometer screws that read to an accuracy of 0·0001 in. The operator changes the position of the part by actuating the two micrometer screws, and brings the other edge or extremity under the cross-line in the microscope. The readings of the micrometer screws give the dimensions measured.

The cross-slide stage is adapted to the use of precision measuring gauges or gauge blocks, which permit the measurement of distances between two points or edges that would otherwise be beyond the accuracy of the measuring screws that actuate the cross-slide.

This toolmaker's microscope, equipped with a 7·5× cross-line eyepiece and 32 mm. micro objective gives a magnification of 42× The 48 mm. objective with adapter, when used, gives a magnification of 21·5×. Other objectives and eyepieces may be used to obtain other magnifications.

A beam of light is guided from the rear of the base of the microscope by a train of mirrors and directed upward through the slide stage and into the field of vision in the microscope. The cover glass, flush with the upper surface of the cross-slide stage, protects the slide from dust, and serves as an object carrier.

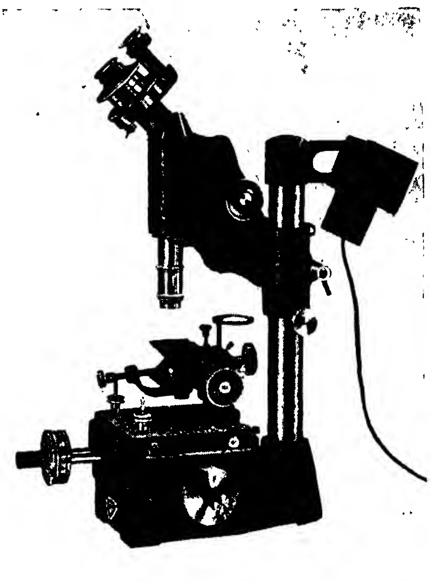


Fig. 77. Toolmaker's Microscope with Protractor Eyepiece Attached

Special Uses for Shop Microscopes. Large numbers of inspection operations are concerned with the nature of surfaces. In finishing and electro-plating a microscope aids in the examination of finished surfaces, for cracks, blisters, irregular deposits and pitting, as well as buffing quality. It can be used in the search for slag inclusions and poor surface conditions of the base metal before plating. On painted surfaces it will reveal quality, uniformity, and distribution of pigment. Half-tones and colour process plates, as well as prints, can be studied for the size, shape, and distribution of "points."

The microscope is valuable in examining cracks, flaws and blowholes. It is ideal for measuring the diameters of small holes as in heading dies, gauges, diameters of impressions in Brinell tests, and for other surface measurements, e.g. depths of "pricks" produced in routine Rockwell tests, etc. Precise mechanical parts may be inspected for wear. The rapid rise of arc and oxy-acetylene welding of machine tool frames, piping, structural members, pressure vessels, and even jigs and fixtures, has led to the need of an inexpensive device for quickly examining welds without always taking recourse to analysis of samples.

2. Contour Measuring or Profile Projectors. Optical projection provides a system of gauging which entirely avoids the necessity for mechanical contact between work and measuring device. This enables the accurate gauging of work which, by using measuring instruments depending upon mechanical contact, would be either exceedingly difficult or impossible to check. Particularly is this the case when checking plate gauges and form tools, and in a less degree, screw threads. Many other gauging operations which offer no serious obstacles to the use of mechanical testing equipment can rapidly and efficiently be carried out by profile projection. In contour projectors we use the principles of optical projection to form a shadow image, i.e. a greatly enlarged silhouette, of an object under magnification. It is a method at once extremely accurate, widely applicable and relatively inexpensive.

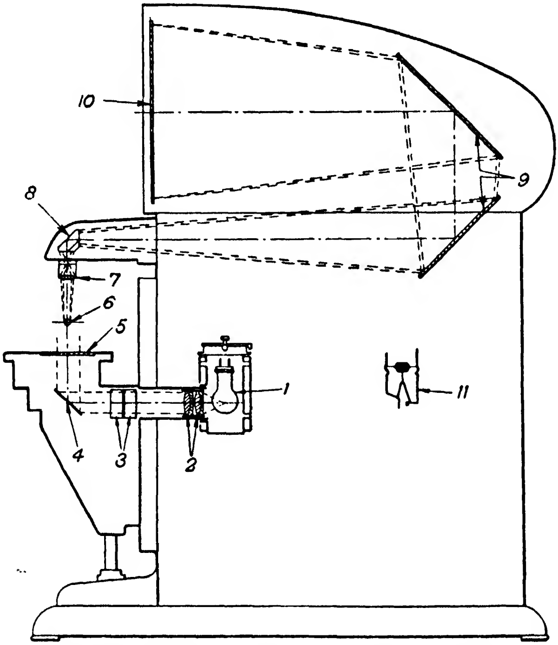


FIG. 78. BAUSCH & LOMB CONTOUR MEASURING PROJECTOR

1. Light source
2. Achromatic condensers
3. Water cells
4. Illuminating mirror
5. Glass stage plate
6. Object
7. Projection lens
8. Roof prism
9. First surface mirrors
10. Translucent screen
11. Diagram of filament and glower arrangement in tungsten arc light source

The image may be **measured** directly, using a white-edged draughtsman's scale; it may be *reproduced* by drawing round its outline, this outline later being used to "match" the image of a second specimen; or the image may be "matched" by comparison *with an outline drawing* made on ground glass or with a drawing or tracing made on translucent paper between the glasses of the screen (Item 10 in Fig. 78).

Perhaps the inspection of screw thread profiles is the work most frequently undertaken in this way.

In projectors the essential parts consist of a *collimator* for producing a parallel beam of light, and an objective for projecting an image of the screw profile on to a screen (to an eyepiece in the case of a microscope).

Large-scale master drawings or templets may be employed for comparison with the outline of the image. "Transparencies" with thread forms to a magnification of 50 diameters are often used. The work to be tested, i.e. measured or compared, is held in centres or vee-blocks, and mirror or prism systems are generally used to reduce the size of the apparatus.

A number of excellent Profile Projectors are on the market, among which for compactness and accuracy the "Matrix Projector" made by Adam Hilger Ltd., London, and marketed by the Coventry Gauge and Tool Co. Ltd., should be mentioned. Then, too, there are excellent Zeiss, Cooke and Taylor-Hobson projectors, some of which we shall describe.

In some designs the lens and mirrors are so arranged that the image of a screw, rack or some other small part is thrown on to a screen just behind the projector. However, where larger components are being handled the projector is generally arranged *outside* a glass-proof cabinet. Mirrors enable the image to be thrown to the top of the cabinet, thus obtaining a high degree of magnification to be obtained when the image is finally projected on to a horizontal table.

A brief description of a contour measuring projector made by the Bausch & Lomb Optical Co. Ltd., will no doubt prove interesting to many inspectors. (See Fig. 78.)

The optical equipment may be described under two headings, viz. the illuminating system and the projection system.

The *illuminating system* consists of the light source (1), a tungsten arc lamp. The light passes to a pair of achromatic condenser lenses (2), whence it is projected in a parallel beam passing through the water cells (3) to the illuminating mirror (4), sending the beam vertically upward through the glass stage plate (5) in the work table, past the object (6).

The *projection system* consists of the projection lens, roof prism, a pair of image reflectors, and the screen. The light travels past the object to the projection lens (7), upon leaving which it passes up to the roof system (8). Leaving the roof prism, the light encounters two flat reflectors (9), after which it travels horizontally towards the operator, to the vertical translucent screen (10) on which the enlarged image is formed. A great advantage of this compact design is that it places a bright, distinct image very close to the operator, and he is thus able to detect very small departures from standard drawings or the reference lines. A plain ground glass screen can be used to observe the image of any part to be reproduced. The outline of the image may be traced upon the ground glass using a sharp hard pencil. An outline can be followed easily to 0·02 in., on the screen, and with care to within 0·01 in. It will be seen that, at 50 × magnification with a departure of 0·02 in. (from the image outline), this tracing will be accurate to 0·02 ÷ 50 = 0·0004 in. on the part projected.

If the glass is washed, dried and "pounced," it will readily take ink.

Thread Measurement and Inspection. By attaching a Screw Thread Accessory to the cross-slide table it is possible to measure pitch (to 0·0001 in.), thread angle (to one minute), helix angle (to one minute), outside diameter (to 0·0001 in.), and root diameter (to 0·0001 in.) by means of the micrometer and dial gauges incorporated in the assembly. On some jobs it may be necessary to take direct measurements of the image by using a white-edged draughtsman's scale. Corresponding sizes on the object can be obtained by dividing these measurements by the magnification.

Ground Profiles of Threads (Fig. 79). Most screw gauges and many other threaded details have their profiles ground instead of leaving the threads as cut in the lathe or thread milling machine. Many specifications for aero parts call for ground threads, especially where difficulties would arise in producing accurate thread forms in special steels. Fig. 79 illustrates the method. Many threads are ground "from the solid."

The accuracy of the contour depends, of course, upon that of the grinding wheel, which has a number of ribs on its rim, each being generated in turn to true form and pitch in relation to the thread being produced. In the first place, and in the periodic dressings of the grinding wheel, a delicate micrometer cam box is set up between the centres which hold the work. The box contains cam, stylus, and holder for diamond dressing tools. The face of the wheel is dressed first. Next a vee-shaped diamond tool is fitted to the holder and the grooves are roughed out. Finally, with a finishing diamond tool, the exact shape of the grooves is generated. See the notes on page 114 also.

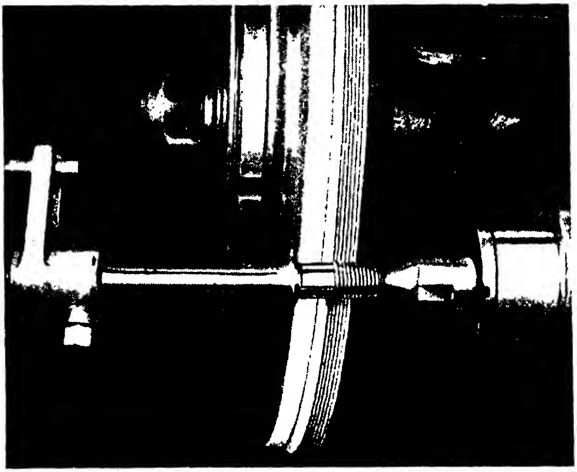


FIG. 79. GRINDING A SCREW THREAD

(By courtesy of Messrs. Rolls-Royce Ltd.)

The "**Taylor-Hobson**" **200 Profile Projector** combines many features worthy of mention, chief amongst which are the large screen image (5-ft. diameter), wide range of magnification (× 20 to × 100), exceptionally large work field combined with freedom from distortion in the projected image not hitherto achieved in any projector. Coupled with this, the projector itself is very robustly constructed and may be adapted to gauge a wide variety of different types of work. The profiles of plate gauges, form tools, screw threads, gear teeth, etc., are projected on to the screen in magnified form where the image may be compared with either (1) a template formed for a master work-piece or (2) a carefully prepared enlarged-scale master drawing. Accurate measurements may be made on the screen; hence, screen measurements can accurately be related to the work because the image is a faithfully magnified reproduction of the object. Projectors employing optical systems not so fully corrected for distortion may only be used as comparators and may provide misleading results if used to obtain actual measurements. The work is illuminated with a beam of collimated light; that is a beam, the rays of which have been rendered substantially parallel by optical means. This system of illumination no doubt produces very accurate images on the screen. It enables very exact measurement and comparison, particularly when projecting parts of substantial thickness.

The magnified image is formed by means of a special series of projection lenses; the magnification is governed by the focal length of the lens in use; the image is of constant size to cover the 5 ft. screen; the work-fields of the various lenses will be seen to be exceptionally large, ranging from 3 in. at × 20 to 0·6 in. at × 100 (see table).

No.	Focus	Magn.	Field
I	2 in.	100	0·6 in.
II	4 in.	50	1·2 in.
III	6⅔ in.	30	2·0 in.
IV	10 in.	20	3·0 in.
V(thread)	4 in.	50	0·5 in.

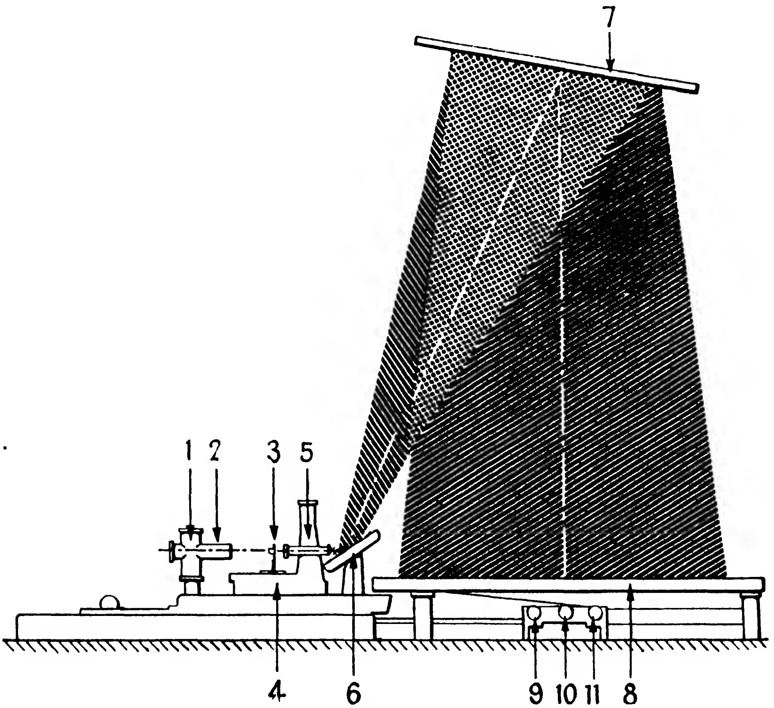


Fig. 79a. Taylor Hobson Projector

Over this field, the image has a guaranteed freedom from distortion claimed by the makers as unique. Thus, a combination giving × 50 magnification will cover a specified work-field with distortion nowhere greater than ± 0·0002 in.; whether projecting profiles of thin flat plates or axial sections of screw threads. The exceptionally large screen image is obtained by using a long throw (approx. 17 ft.), and the beam is reflected from two mirrors as shown in Fig. 79a. This keeps the structure of the instrument compact and also enables the use of a horizontal screen. This is a great help when measurements of the image are made.

The massive framework of the projector renders it immune to the effects of vibration; the mirrors are optically flat and are metallized on the front face. Thus the utmost attainable accuracy in the projected image is achieved.

The work-table of the instrument is of large size and capable of accommodating quite large parts. Movements are provided for placing the image suitably on the screen and these are controlled remotely by three knobs beneath the screen. One of these knobs is used to focus the image whilst the other two control the position of the image in two directions at right angles.

Accessory equipment is available in the form of special fixtures for holding centred work, plate gauges and threaded parts. An auxiliary work-table, with micrometer control reading direct to 0·0001 in., provides tilting and swivelling movements so that work can be presented at an inclination to the optical axis of the projector (e.g. threaded work of large helix angle).

Of special interest is the equipment **for measuring screw threads.** Axial sections of threaded work (magnified × 50) can be projected by means of a special thread lens (Combination V; see table) which allows the collimated illuminating beam to be inclined to the optical axis of the projector so as to illuminate the thread along its helix. Thread-form measurements can be made accurately by this means, and these are greatly assisted by the use of standard thread-form templates in conjunction with the slip gauge carrier and screen micrometer. The slip gauge carrier enables a pair of lines to be projected on to the screen at the same time as the screw thread. The separation of these lines is controlled by means of slip gauges. Small discrepancies between the image and the drawing on the screen can be very accurately measured by means of the screen micrometer.

Profile projection provides, especially in the inspection of gauges and tools, a rapid means of accurate measurement. It can also be very successfully adapted for the rapid examination of mass-produced parts where it is of special value when the work has several dimensions which must be gauged.

Vickers Contour Projector (Fig. 79B). Marketed by Cooke, Troughton & Simms, Ltd., of York.

Reference to Fig. 79B will show how very compact is the design. Its principal uses are—

1. The measurement of magnified silhouettes of templates and other plane objects, or their comparison with translucent masters drawn on an enlarged scale.
2. The measurement of screw threads, or their comparison under magnification with master screw thread templates.

The projector is so designed that the object and image planes are close together. All controls may be manipulated whilst the image is under observation. Since projection is from *beneath* the screen the observer does not tend to produce shadows across the projected image when taking measurements with a rule, protractor or the like.

The illumination is sufficient to allow the use of the instrument in a well-lighted room, whilst, when necessary, a hood may be used to cut off stray light from the screen. The instrument is constructed to project an image whose size bears a fixed relationship to that of the object, i.e. exactly 10, 25 or 50 times.

The dimensions of the object may be determined in two ways—

1. By measuring the projected image and dividing the result by the appropriate magnification factor, or
2. By translating the projected image in relation to a fiducial line on the projection screen, and by noting on the micrometer screws of the measuring stage the value of the movements necessary to bring this about.

In the first method, measurement of the image may be made conveniently with a glass scale, or from a template made to the appropriate scale. Such templates may be produced photographically from a master component, drawn on tracing paper, or formed out of sheet metal.

The **Westminster Optical Projector** is a very compact instrument manufactured by J. E. Baty & Co. It is self-contained, very easy to manipulate, and can be plugged in to a lamp socket.

Alignment Telescope for Aircraft Assembly, etc. The increasing dimensions of modern airframe sections brought about the necessity for providing a more accurate and rapid method of reference to jig alignment. The well-known Taylor-Hobson telescope was designed for testing the parallelism of bearings and the departure of the axes of the bearings from coincidence. Essentially it consists of a telescope and collimator as shown in Fig. 79c. Want of parallelism amounting to one part in 30 000 and lack of alignment of 0·01 in. at 50-ft. distance can readily be measured. Want of parallelism of one part in 20 000 is normal working accuracy. This telescope is successfully used in testing alignment during the construction of the jigs required for the assembly of large aircraft components, such as centre sections, wings, ailerons, etc. In mechanical engineering it is used in testing the alignment of cylinders, guide bars and axles of locos., engine stern tube and tunnel bearings for steam and motor vessels, etc.

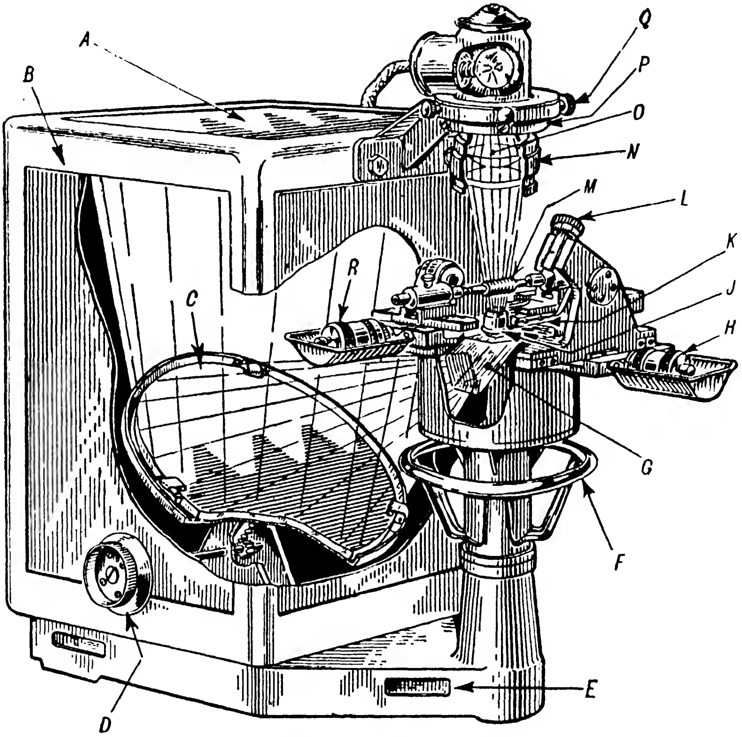


FIG. 79B. VICKERS CONTOUR PROJECTOR

A = Projection screen.
B = Camera.
C = Mirror.
D = Adjustment for magnification.
E = Cast-iron base.
F = Focusing wheel.
G = Roof prism.
H = Transverse micrometer.

J = Projection anastigmat.
K = Ball-bearing slides.
L = Helix angle micrometer.
M = Screw thread under test.
N = Condenser spiral focusing sleeve.
O = Condenser.
P = Centring screws for condenser.
Q = Centring screws for lamp.
R = Longitudinal micrometer.

Optical Flats. These are cylindrical discs of ground glass or quartz used for checking the *flatness* of lapped surfaces of slip gauges, micrometer anvils, etc. Their opposite flat faces are ground plane and parallel to limits of 0·000005 in. (5 one-millionth parts of an inch) and to tolerances of 0·00001 in. for thickness.

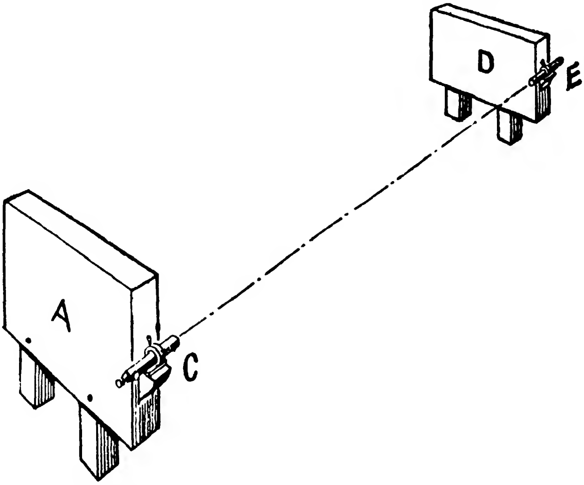


Fig. 79c. Line Diagram of Taylor-Hobson Alignment Telescope in Use

A is one end of the assembly jig on which is mounted the telescope. At the required distance is the other end of the jig *D*, on which is mounted the collimator in a manner similar to the telescope on *A*. By making observations of the collimator scales through the telescope, direct readings of alignment discrepancies may be made, from which the necessary adjustments are easily carried out.

Fig. 79d shows a P.V.E. optical flat for testing surfaces of slip gauges, micrometer anvils, and other lapped surfaces. Scratches on the surface of the optical flat do not impair the accuracy, as they do not raise a jagged edge, but they certainly make observation more difficult.

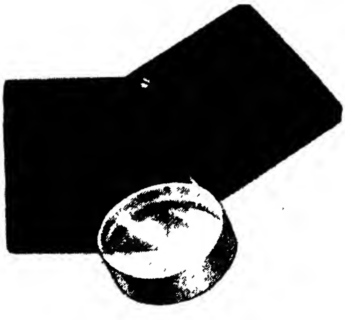


Fig. 79d. P.V.E. Optical Flat

The Pitter Gauge and Precision Tool Co. Ltd. supply these flats singly or in sets of three. Readers with good fitting or tool-making experience will realize that three flats may be tested within themselves for flatness in the same way as surface plates are tested and made truly flat in sets of three.

By bringing the flat into contact with the surface to be checked, "interference bands" or "fringes" are shown through the flat. The manner in which these "bands" appear, e.g. whether straight, curved, regularly spaced, etc., reveals the state of the surface under inspection. If the interference lines appear straight and parallel the work surface to which the optical flat is applied is probably "truly flat," i.e. flat to within a hundred-thousandth of an inch. If the surface to be tested is convex or concave, the bands will be curved and irregular, forming in fact a contour map of the surface under inspection. The flat must not be wrung on to the surface to be tested as this would probably cause the flat to become distorted closely to the form of the work surface. The test has limited usefulness for it reveals nothing except on highly accurate surfaces. Then, too, the flat should only be used in the shadow of a coloured screen which "filters back" all light except that of one wavelength, that is a screen which transmits "monochromatic" light.

Other Tests of Flatness

For less accurate work a simple test of flatness is to apply a straight-edge to it and to look at a strong light between the straight-edge and the surface of the work. Very small clearances—say of "a ten-thousandth"—can readily be seen. If the work to be tested is small it could be applied to a "surface plate," the surface of which has been lightly smeared with a colouring substance such as red lead or printer's ink. The disposition of this colouring on the surface of the work to be tested reveals the "high points." This is the method commonly used in the fitting shop.

CHAPTER IX

SOME COMMONLY USED GAUGES

GAUGES. To ensure that work (especially parts which are mass-produced and destined to be interchangeable) falls within specified limits, standard gauges have come into general use. They are usually known as "go" and "not go" gauges. (See Figs. 80 and 81.) These are made with tolerance allowances, i.e. clearly defined and permissible departures from the exact nominal size. These are fine enough, as we have seen, to permit of the interchangeability of the parts, but they do not make too severe demands on the tooling operations. In this system the workman may be said not to measure, but to gauge; the limits and tolerances being included in the gauge.

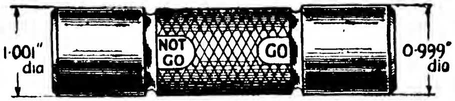


Fig. 80. Simple Limit Plug Gauge

The cylindrical "GO" end is usually longer than the "NOT GO" end. See Fig. 2.

The greater the efficiency of the gauges, whether for high mass-production or merely for small-lot production, the complete interchangeability of each part will be more closely achieved. In the manufacture of aero engines *quality* is of first importance. Therefore limits are "tight" and the inspection of components and fittings is necessarily fastidious.

Fixed-size gauges can be classified broadly into "cylindrical" and "snap." **Snap gauges** are flat and thin with small areas of contact. **Cylindrical gauges** fill a hole or encircle a shaft, whereas snap gauges measure only a narrow zone. The former have declining popularity; the latter are used increasingly. One reason is that the surfaces in contact being larger in one case than the other the test is not so refined. A snap gauge, properly used, will detect a variation that a cylindrical one will not show. This harmonizes with the common preference shown by skilled men for narrow points, rather than wide ones, on ordinary calipers.

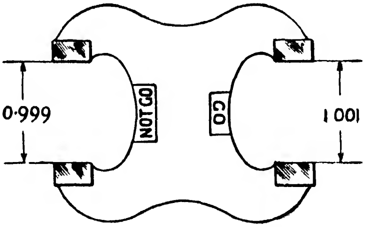


Fig. 81. Simple Limit Snap Gauge

These may be considered fine distinctions, but the function of fixed gauges is to deal with these. The dimension 1/1 000 in. reads like a fine dimension but in fact it is coarse in precision work. A difference of that extent in a shaft and its bearing would be a slack fit. Such fits are of course in certain instances, but the allowance necessary to achieve them is not nowadays left to the skill of the individual workman with the terse instruction "running fit," but is embodied in the *limit dimensioning of the drawing* and controlled by the gauges which permit only those jobs to be passed which have exactly specified variations from absolute "nominal" sizes to suit any kind of fit desired.

The **ring gauge** is used to gauge a shaft or bar whilst the **plug gauge** (Fig. 80) is used to gauge a hole. In Fig. 81 the **snap gauge** is used to gauge a shaft of 1 in. nominal diameter. The "go" gauge is made to the high limit and the "not go" to the low limit. The "go" gauge should therefore pass over the shaft, whereas the "not go" should not. In the case of the plug gauge shown in Fig. 80 the "go" end is made to the low limit of the hole and should enter. The "not go" is made to the high limit and should not enter. The "go in" end is often made longer than the "not go in" to enable the workman to recognize

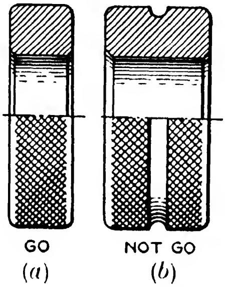


FIG. 82. RING GAUGES

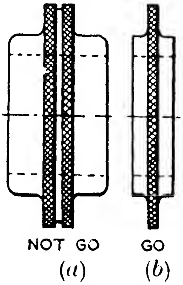


FIG. 83. RING GAUGES

(See descriptive notes)

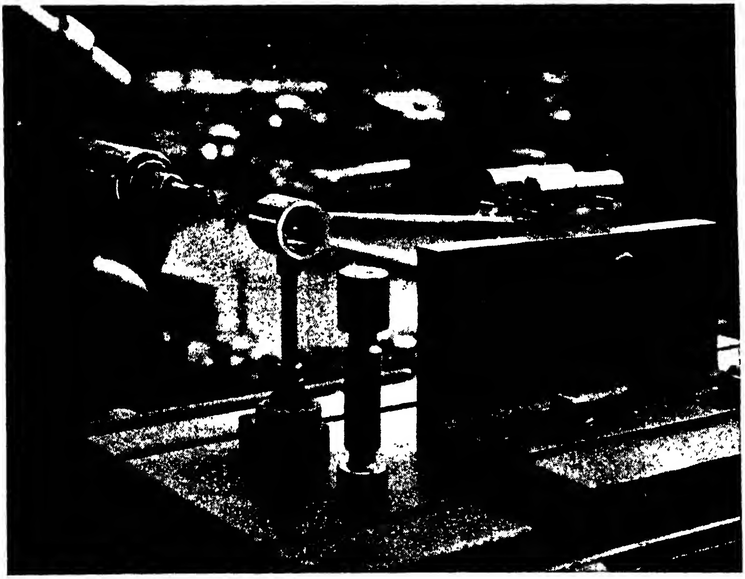


FIG. 84. GRINDING THE SMALL END OF A CONNECTING ROD

Note the limit plug gauge used by the machinist it at a glance. The ends of cast-steel plug gauges are hardened, tempered and ground (if of mild steel they can only be case-hardened) within a limit of accuracy to nominal size of 0·0001 in. As mentioned previously, they are now used much less than the limit gauges of snap type, especially in the large sizes. Machinists find snap gauges very convenient for gauging cylindrical work without having to remove the latter from the machine. This is not always possible with ring gauges. The fixed type of gauge is generally used to check the high and low limits. Simple and reliable they are widely used for checking large quantities of components made either to close or coarse tolerances. A gauge made to the mean of the two dimensions may also be provided to test the fit. Dimensions are always stamped, engraved, or etched on the gauges.

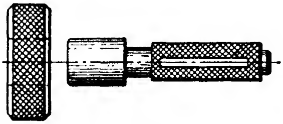


FIG. 85. SIMPLE PLUG AND RING GAUGE

In **Figs. 82** and **83** are shown various designs for solid, or one-piece **ring gauges.** Fig. 82 (*a*) is suitable for diameters up to 2 in. or thereabouts. The "not go" ring (*b*) is usually the longer of the two and may be distinguished easily from the "go" ring by the annular groove or some similar means. The rings in Fig. 83 are for larger sizes. For even larger work the gauges may be provided with two or more radial handles.

The Standard Plug and Ring Gauge (Fig. 85). In Fig. 85 we show the nominal size, single-ended plug with its ring gauge of common design for diameters up to say 1 in. This is of little use to the machinist in connexion with interchangeable manufacture. It is carefully made to one standard size (to within 0·0001 in. at least) and can be used for highly skilled work in the tool-room and Inspection Department, where, among other uses, it can be employed for setting micrometers and other measuring instruments. It can also be used as a **reference gauge** for

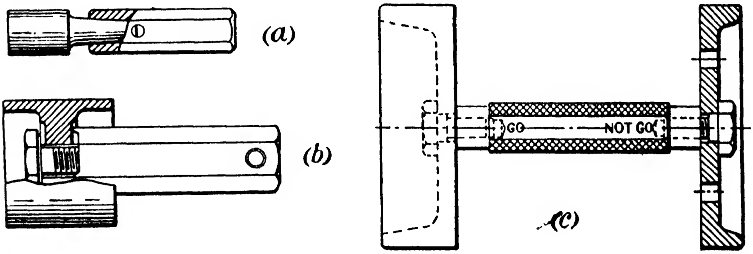


FIG. 86. PLUG GAUGE DESIGNS
(See descriptive notes—pages 105 and 108)

checking working and inspection gauges. The diameter of the gauge is exactly the size stamped on the handle, although on a new gauge it may be "plus," and *never* minus, a tenth of a "thou" to allow a small margin for wear. This margin is known as "wear allowance."

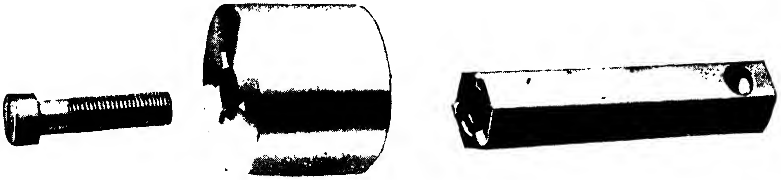


FIG. 87. TRILOCK PLAIN PLUG GAUGE
(*By courtesy of Coventry Gauge and Tool Co. Ltd.*)

Taper Lock Plug Gauge (Fig. 86 (*a*)). Up to 1·510 in. diameter the Coventry Gauge and Tool Co. Ltd. supply both single- and double-ended plug gauges with renewable ends. The latter have taper shanks fitting in a taper hole in the handle. When properly assembled the gauge has all the rigidity of a solid gauge.

Trilock Plain Plug Gauge (Fig. 87). This is a popular "Matrix" design marketed by the Coventry Gauge and Tool Co. Ltd. for gauges from 1·510 in. to 8·010 in. diameter. Three wedge-shaped locking prongs on the handle are forced into corresponding grooves in the gauging member by means of a central screw. The gauge is thus self-centring and has a positive lock on the handle. Grooves are provided at both ends of the gauging member so that when one end becomes worn it can be reversed in the handle.

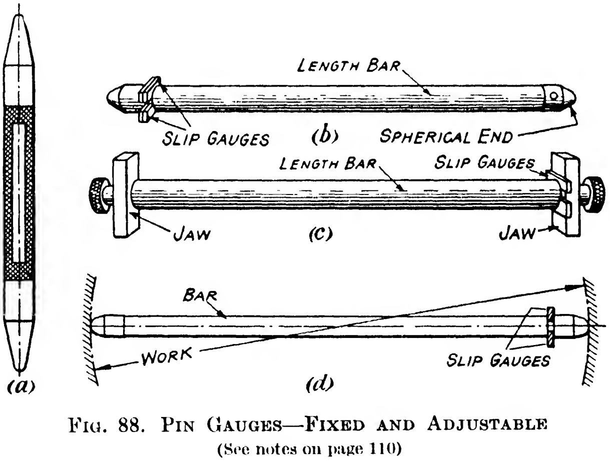


FIG. 88. PIN GAUGES—FIXED AND ADJUSTABLE
(See notes on page 110)

Single-ended Limit Plug Gauges consist of a cylinder of hardened steel having two slightly different diameters, the smaller of which, the

"GO" portion, is at the front, or entering, end of the gauge; the larger diameter ("NOT GO") being at the back.

This type of gauge is suitable for "through" holes where the "GO" end passes out of the back of the hole, allowing the "NOT GO" end to engage the hole. If the hole is of the correct size the larger "NOT GO" diameter arrests further progress of the gauge into the hole, showing that the hole is within the tolerance. Gauges of this type cannot be used on "blind" or "shouldered" holes. Thus their use is limited, and therefore they are not in general favour.

Double-ended Limit Plug Gauges. See Fig. 2 (*b*). These are the most common of all plug gauges, consisting of two hardened steel cylinders joined by a common handle. The longer cylinder, and smallest in outside diameter, is the "GO" end, and the shorter and larger diameter cylinder the "NOT GO" end. The difference between the sizes of the "GO" end and the "NOT GO" end are determined by the tolerance on the hole which the gauge will be used to check.

Suppose the hole to be gauged is 1 in. dia., minus nothing, plus a "thou," i.e. tolerance is 0·001 in., then theoretically the "GO" end of the gauge will be 1 in. dia. and the "NOT GO" 1·001 in. dia., but in practice there are two further points to be considered, viz. "**wear allowance**" and "**manufacturing error,**" in making the gauge itself. If the "GO" end were made exactly 1 in. dia., the first time it was used and passed through a hole wear would occur and it would become undersize. To overcome this the "GO" end could be made slightly larger than the smallest size of the hole allowed by the tolerance. This very small increment in diameter is known as the **wear allowance.** There are different opinions as to the amount of this allowance, but many firms follow the Air Ministry specification of 10 per cent of the tolerance, so that in the case of the gauge discussed, the allowance would possibly be $\frac{1}{10}$th of a "thou," or the "GO" end of the gauge, when new, should be 1·0001 in. dia. Had the tolerance on the hole been "half a thou," then the wear allowance would be "half-a-tenth of a thou." As the "NOT GO" end theoretically never enters the hole, no allowance on its diameter is made for wear.

The amount of wear allowance is often the cause of differences of opinion in the works between those responsible for the purchase and maintenance of the gauges. Of course the larger this is made the longer will the gauges last before they have worn undersize, thus keeping the gauge expense account down. The matter does not end there, however, for it must be obvious that the larger the wear allowance the less actual machine-shop tolerance is available.

In practice, of course, it is not customary to endeavour to make a gauge "dead on," simply because the cost would be prohibitive. Therefore for economical production some **manufacturing tolerance** must be arranged. In practice it varies with the tolerance on the hole and its diameter, 5 per cent of the tolerance being common. If we apply this to the gauge under discussion it would pass inspection if the "GO" end were 1·00005 in. to 1·0001 in., or, in other words, "half a tenth of a thou" is allowed as a manufacturing tolerance on this particular job. It should be noted that error must never be on the plus side of the wear allowance; always it must be on the minus side. Thus in the best condition the maximum wear allowance is one-tenth (of a thou) and the minimum allowance half-a-tenth of a thou on this job. In the case of the "NOT GO" end this is acceptable if it is exactly the maximum size of the hole allowed by the tolerance to minus half-a-tenth (of a thou) under this size.

Under ordinary workshop conditions the ordinary double-ended limit plug gauge has the following advantages:

1. It is comparatively inexpensive.
2. It can be checked for size with a high degree of accuracy by comparatively unskilled labour.
3. It is foolproof and cannot be tampered with.
4. It manifestly represents the part that is going into the hole, so that if the gauge will enter the component will enter.

Plug Gauge of Plate Type (Fig. 88A). This shows a toolroom drawing of a gauge used by the De Havilland Aircraft Co., Ltd. The material list specified mild steel case-hardened and ground all over. In sending it for reproduction the Production Manager, H. J. Nixon, Esq., supplied the following interesting notes—

You will note that the tolerance between "GO" and "NOT GO" is 0·001 in. on the component. As it is customary to allow the gauge maker 10 per cent of the component tolerance this reduces the gauge manufacturing tolerance to 0·0001 in. This type of gauge, though fairly easy to manufacture and fairly reliable in use, has a short life—as any wear on the gauge takes it beyond the gauge tolerance. It is customary then to reduce the diameters and have the gauging faces chromium-plated and re-ground.

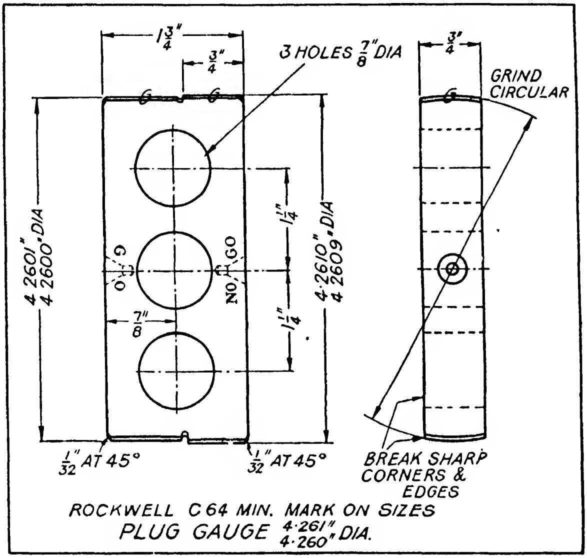


FIG. 88A. PLUG GAUGE OF PLATE TYPE

Checking Roundness. Plug gauges are used for checking the dimensions of holes, but they do not check their roundness. A hole may be elliptical, in which case the plug will not enter until the smallest diameter of ellipse is at least as large as the diameter of the plug. Meanwhile the largest diameter of the hole might even be greater than the "NOT GO" diameter of the plug.

However, under modern production conditions plug gauges serve most purposes, and holes produced are usually as nearly cylindrical as matters. It is well to mention, nevertheless, that there are certain geometrical "constant diameter" shapes (other than circles) which, considered as sections of a shaft, would give identical micrometer readings over any two points. This type of "shape" or "figure" may have any odd number of lobes, and a check with a micrometer would fail to reveal that the shape was not truly circular. Parts finished on centreless grinders and in some lapping operations may have a lobed "constant diameter" shape but as the error is usually very small it is rarely of practical significance. A typical three-lobed "constant diameter" figure is shown in Fig. 88B. It can be drawn by a "six-arc, three-centre" method, commencing from the equilateral triangle shown. Appreciable out-of-roundness of a shaft can be tested by placing it in a pair of V-blocks and rotating it under the plunger of a dial indicator or "clock gauge."

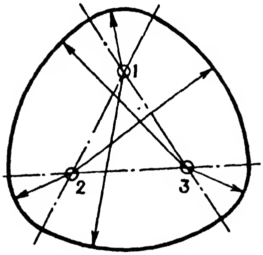


Fig. 88B

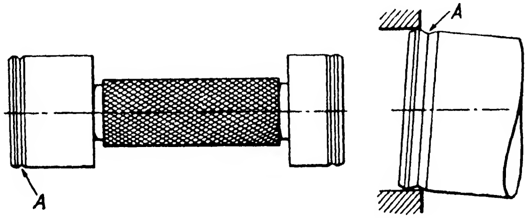


Fig. 88C. Pilot Plug Gauge

Larger Plug Gauges (Fig. 86). In the Coventry Gauge Trilock series plug gauges over 2½ in. diameter have the gauging member recessed for lightness. Fig. 86 (*b*) shows a Trilock "go" gauge (2½ in. to 8 in. diameter).

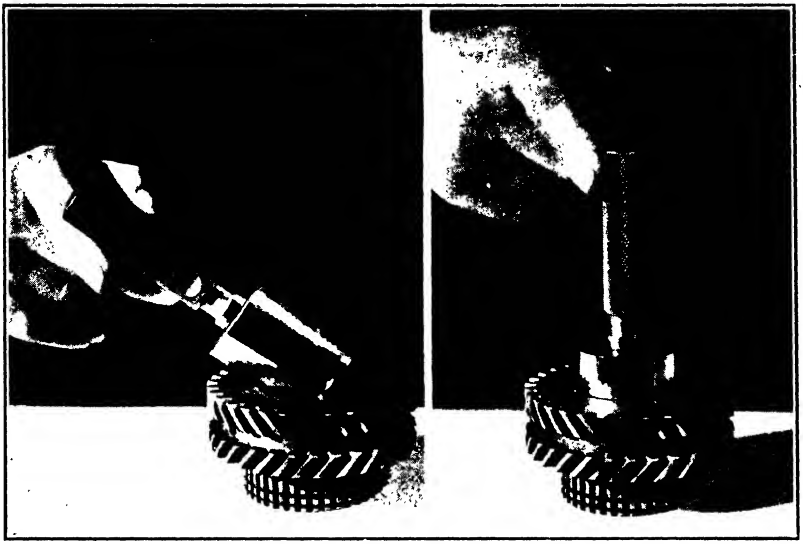


Fig. 88D. Using the Pilot Plug Gauge

The gauge is allowed to rest on the edge of the bore, as shown at the left, and raised until it slides into the bore automatically, as shown at right.

Fig. 86 (*c*). This shows another design for larger diameter limit plug gauges. Unduly heavy plugs tend to tilt and lock themselves in the component, perhaps scoring the bore and damaging both plug and work. They are therefore lightened as far as possible, steel handles being hollowed out or replaced by light alloy handles; the ends or inspection pieces being liberally recessed and, in some cases, drilled.

The Pilot Plug Gauge. There is more in the rapid and successful use of a plug gauge than meets the eye. When the tolerance on the diameter of a bore is small some difficulty is frequently experienced in inserting a plug gauge into a hole—especially if the component is awkwardly placed. In removing a jammed plug from a hole time is wasted, the gauge may be damaged and, if the component is mounted on a machine fixture, its setting may be disturbed. *The Pilot Plug Gauge is so designed that it enters a hole easily.*

Its design is based on the fact that after a plug gauge has been in use for some time a brightly polished annular ring may be seen about $\frac{1}{16}$ in. from the end of the gauge. This marking is caused by the jamming action. So as to permit free entry of the plug gauge, therefore, an annular groove is provided at this place on the curved surface of the plug, as indicated at *A* in Fig. 88c.

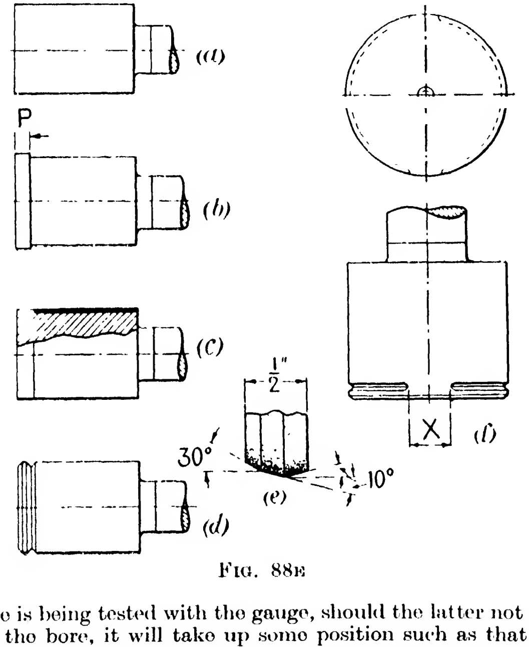


FIG. 88E

When the bore is being tested with the gauge, should the latter not be absolutely co-axial with the bore, it will take up some position such as that shown exaggerated in the diagram on the right. The edge of the hole then engages the chamfer of the groove *A* and the gauge is brought into line with the hole, jamming being avoided.

That portion of the gauge between the groove *A* and the end face serves as a *pilot*. The ease with which a Pilot Gauge can be inserted in the bore of a transmission gear is shown in Fig. 88D. If the gauge is allowed to rest on the edge of the bore at an angle, and is then raised, it automatically lines up with the bore and slides in, should the bore be of the required diameter. In practice the gauge is pushed into the hole in the normal way, no "feeling" being required.

Pilot gauges can be obtained with a hard **chrome-plated finish,** the advantages of this finish being that it is very considerably harder than the usual materials gauged, it has a lower coefficient of friction, and it offers high resistance to corrosion. To avoid any possibility of the chipping of this rather brittle plating, however, the pilot portion of the plug is not plated. The body of the plug is mild steel, case-hardened, and the case is left exposed at the pilot end. The plating on the main portion is thus protected. The method of producing the plated gauge is shown in Fig. 88E. The blank is turned to the form indicated at (*a*), leaving the outside diameter from 0·012 to 0·015 in. oversize. Then after hardening, it is ground to the form shown at (*b*), the land at *P* being ⅛-in. for gauges up to 2 in. and $\frac{3}{16}$-in. for gauges larger than 2 in. The body of the gauge is at this stage ground to 0·004-in. below nominal size. The blank is next chromium-plated, and grinding and lapping operations follow, at which the gauge is reduced to finished size. During the latter operations the plating is removed from the land, but remains on the body of the gauge, as indicated in the partly-sectioned view at (*c*) in Fig. 88E. Finally, the end of the gauge is chamfered and the annular groove is produced, as shown at (*d*) by means of a plunge-cut with a grinding wheel, the form of which is illustrated at (*e*).

When required for gauging blind holes, the form of the Pilot Gauge may be modified as shown by the drawing in Fig. (*f*). In this instance the groove does not encircle the gauge completely, but is in two parts separated by the lands, the width of which, as measured on the periphery of the gauge, is equal approximately to one quarter of its diameter.

It may be noted that existing gauges can readily be modified by grinding, but the Pilot Gauge Co. (Coventry), point out that this is not permissible without their consent, the principle being covered by their patent.

Pin Gauges (Fig. 88). These are pins having rounded ends, the finished overall length being ground accurately to size. They may be made in pairs as "go" and "not go" gauges.

The Newall Engineering Co. Ltd. market sets of pin gauges which can be adjusted within very fine limits. Then, too, the Coventry Gauge and Tool Co. Ltd. market sets of combination length bars of remarkable accuracy. Spherical ends can be attached so as to convert the length bars into pin gauges for internal measurements. For measurements involving decimal parts of an inch, slip gauges can be inserted under the spherical ends. For external measurements it is possible to attach flats, jaws, or bars to the ends of the length bars. The bars are arranged to give sizes in ½ in. steps, intermediate sizes being obtained by inserting slip gauges between the end of the bar and the attached jaw. The idea is shown in Fig. 88 (*b*) to (*d*), but the detail is not necessarily identical with that in the Coventry "Matrix" design. The reader may advantageously refer back to pages 84 and 85 where P.V.E. End Bars, Spherical Ends, Jaws, etc., are described. They are, of course, capable of the same useful service as the other types mentioned in this paragraph.

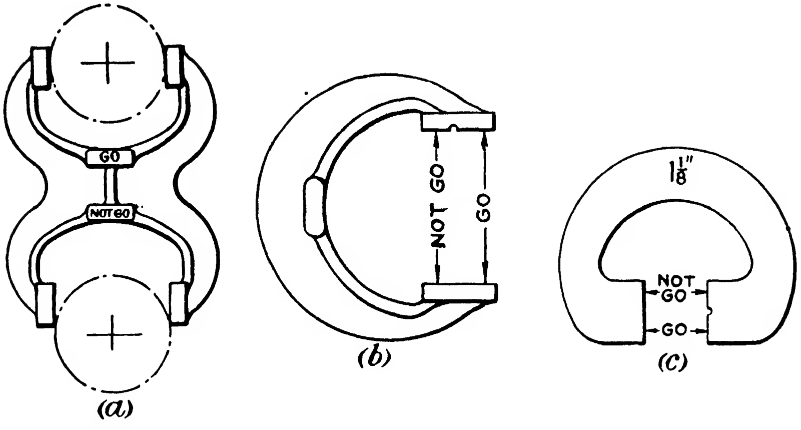


FIG. 89. EXTERNAL CALIPER OR SNAP GAUGES FOR QUICK CHECKS OF LIMIT DIMENSIONS

The length of a pin gauge can be compared with a setting obtained by means of a pile of block and slip gauges wrung together as shown in **Fig. 89A.** In work of this kind a light well-developed sense of touch is important. The pin is held at its lower end and whilst the upper end is carefully rocked through small angles until the sense of touch demonstrates that *A* just grazes *DE* in one spot. When testing a pin gauge in this way, or when using the gauge to test a bored hole up to, say, 6 in. dia., a skilled inspector can rely upon his sense of touch to detect a tightness of fit as close as 0·0001 in.

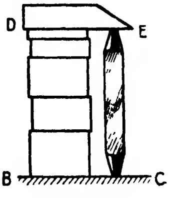


FIG. 89A

External Caliper or Snap Gauges (Fig. 89). Types (*a*) and (*b*) are usually case-hardened low-carbon steel stampings with the jaws hardened and ground to size. For higher accuracy the jaws are lapped. Shafts and other cylindrical jobs manufactured to standard allowances are readily checked to size by these simple gauges. At (*c*) is shown a "horse-shoe" plate caliper gauge made of cast steel, hardened, tempered and ground. This type, too, are often made double-ended.

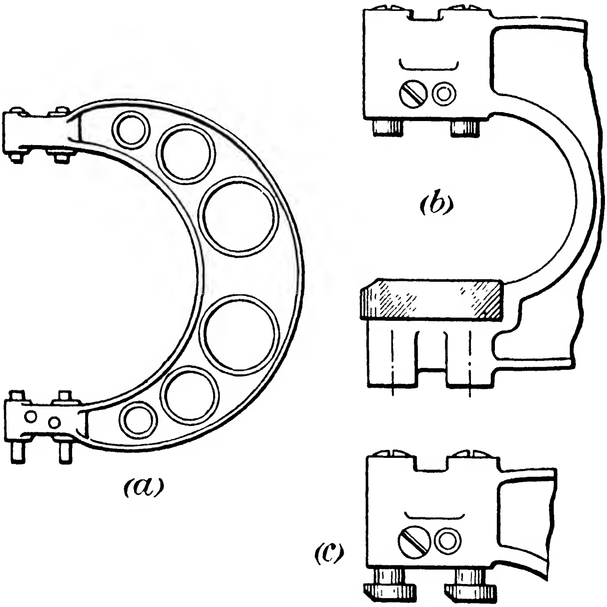


FIG. 90. DESIGNS OF ADJUSTABLE "GO" AND "NOT GO" LIMIT CALIPER GAUGES

Adjustable External Limit Gauge. For larger sizes it is often advisable to have "go" and "not go" points on the same gauge as shown in Fig. 90 (*a*), and to make provision for their adjustment to give a range of limits. This method avoids a great accumulation of fixed gauges by firms requiring several sets of limits for different classes of fits. In setting the anvils or points (which are fine-pitch screws) the use of limit reference bars (see Fig. 91) is common. These bars are ground cylindrically on the ends within 0·0002 in. of standard. The snap gauges are also readily adjusted by reference to built-up sets of precision blocks and slip gauges. (See Figs. 73 and 74.)

Fig. 91. A Newall Limit Bar

When adjusted to requirements the anvils can, on most designs, be locked and sealed to prevent unauthorized alteration. Of course the "go" or high limit size, is represented by the front two points (or anvils) at the mouth of the gauge, and the "not go" by those at the rear. Limit caliper gauges having broader measuring surfaces are indicated at (*b*) and (*c*) in Fig. 90.

Taper Gauges. Gauges for inspecting taper holes and shafts are usually very simple, the first *test of correct taper* being made by assembling the gauge and component and seeing if "rock" occurs. Where there is no readily detected "rock" the male component may be smeared with prussian blue or fine chalk and assembled with the female gauge. Parts in contact are revealed if the pieces are given a slight rotatory motion. It is necessary also to *check the relative longitudinal*

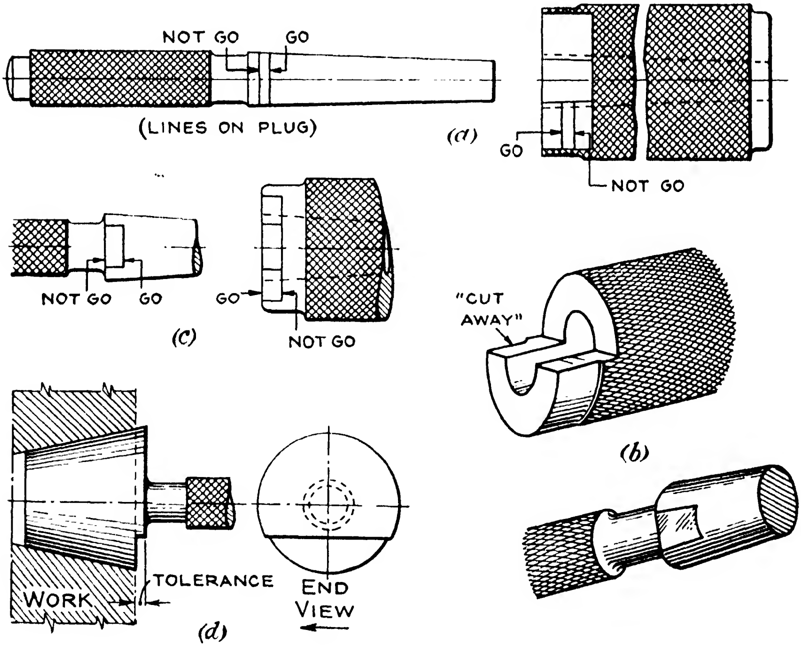


Fig. 92. Some Taper Gauges
(See the relevant descriptive notes)

positions of the parts. Generally the largest diameter is taken as the standard size, but there are exceptions. The tolerance is not usually held to very close limits. Where the relative longitudinal position of the two points is not highly important the plug may have two lines on it.

Thus at (*a*) in Fig. 92 the plug has two lines marked "go" and "not go" respectively. In setting the limits the "go" position on the plug should correspond exactly with the "not go" position on the ring. In other words, when the ring is placed over the taper plug the "not go" line on the ring should coincide with the "go" line on the plug. The taper ring gauge is often cut away to enable the "go" and "not go" lines to be seen more clearly. At (*c*) both the plug and ring have milled flats, the distances between the ends of the flats representing the tolerance on the work. This is also shown at (*d*).

Making the Gauges. When a taper plug is to be made to a standard taper, e.g. Brown & Sharpe, Morse, Jarno, etc., the plug is made to the exact length specified and the largest and smallest diameters on the plug are checked to very close limits. The same applies, of course, to the ring. When a plug is made for other than what is known as a "standard taper," the size of the large end and the amount of the taper are the only two governing points.

GENERAL NOTES

1. A "go" gauge should assemble freely (without forcing) with the component to be tested.

2. A "not go" gauge should not assemble with its component. "Not go" effective diameter screw plug gauges may be allowed to screw one, or perhaps two, turns at the most into the screwed hole to be tested.

3. All "go" gauges should be re-examined regularly as a check on their wear. It is important that workshop gauges be discarded at once when they begin to pass components outside the limits specified.

4. Limits laid down on drawings for components and gauges are intended to apply at the standard temperature of 68° F. When gauging components in, or straight from, the machine, care must be taken that they are not overheated. This is especially important in the case of brass, aluminium, and light alloy components having a high coefficient of expansion in relation to steel.

Three Classes of Gauges. (Also discussed in Chapter III.)

1. **Working Gauges** (or production gauges) for shop use as a control during actual production of components. So as to provide a margin of safety they should therefore be of such size as to check the component to limits which are slightly inside the drawing limits.

2. **Inspection Gauges** for final checking of components.

3. **Reference Gauges** for checking and adjusting working and inspection gauges.

Manufacturing Tolerances on Gauges. The gauge maker must of necessity work to very close limits and the National Physical Laboratory has drawn up a specification dealing with limits for gauges. Cylindrical gauges may be made in one of two Classes *A* or *B*, snap gauges being made to a single standard grade. The pamphlet "Gauge Testing" is obtainable from the Director, National Physical Laboratory, Teddington, Middlesex.

LIMITS OF ACCURACY FOR CYLINDRICAL PLUG AND RING GAUGES AND SNAP GAUGES

Diameter of Gauge	Plain Cylindrical Plug or Ring		Snap Gauges
	Grade *A*	Grade *B*	Standard Grade
Up to 1 in. . . .	± 0·00005 in.	± 0·0001 in.	± 0·0001 in.
From 1 in. to 2 in. .	± 0·0001 in.	± 0·0002 in.	± 0·0002 in.
From 2 in. to 4 in. .	± 0·00015 in.	± 0·0003 in.	± 0·0003 in.
From 4 in. to 6 in. .	± 0·0002 in.	± 0·0004 in.	± 0·0004 in.

GAUGE-MAKING MATERIALS. A gauge used frequently in engineering work must be made from material able to withstand wear caused by constant rubbing against other metal. Then, too, the metal should have little tendency to grow or to shrink. Plug and ring gauges in the smaller sizes are often made from steel with a carbon content of *not less than* one per cent. This *cast steel*, as we have seen, can be hardened throughout. In the larger sizes gauges are often made from low-carbon steel which can be case-hardened. Hardened steel can be ground and lapped to a very fine finish. Even larger gauges of various forms may be made from cast iron, the measuring and wearing parts sometimes being lined with hardened steel.

Changes in size of well-used workshop gauges usually arise through wear, but reference gauges may grow or shrink in time even if rarely used.

A gauge should be far more wear-resisting than the material of the job it "gauges." It is obviously foolish to gauge a case-hardened hole with a case-hardened gauge of equal hardness. If grinding grit is present it will damage the gauge as much as the hole. **Chromium plating** yields a gauging surface which wears less than hardened steel, is less liable to corrosion, and has the important advantage of having a very "slippery" surface. Wearing parts for gauges are now also being made from stellite and tungsten carbides—materials mainly employed for high-speed metal cutting—but gauges made from such materials are necessarily expensive in first cost. Maintenance costs, however, are considerably less on hard long-wearing gauges, and gauge wear allowances can be reduced to an absolute minimum.

Thread Ground Pieces. Changes in dimensions of threaded plugs, taps, etc., after hardening are obviated by the newer method of grinding the threads after hardening the blanks. This is the method now used by all the larger makers. Otherwise the threads were cut in a lathe, using good quality carbon steel. The exact magnitude of the contraction (about 0·2 per cent), or the expansion (0·1 to 0·2 per cent) being known, the pitch of the threads had to be cut longer or shorter so as to arrive at the correct pitch after hardening. This is still done where thread-grinding machines are not employed. It is advisable to reduce strains by annealing the blanks after rough machining. There are some relatively expensive steels on the market said to show practically no appreciable difference in pitch or diameter after hardening. Some threads with small errors are corrected by grinding after being machined and hardened. Commercial tolerances for ground thread taps may be taken as a maximum pitch error of ± 0·0005 in. per one inch of thread. Other notes on thread grinding are given in Chapter VIII.

CHAPTER X

THREADS AND THEIR MEASUREMENT

THE cross-section of a thread varies according to its use, the two main "families" being *square* and *vee*. Among the vee threads are Whitworth Standard (B.S.W.), British Standard Fine (B.S.F.), British Standard Pipe (B.S.P.), British Association (B.A.), U.S.A. Standard, Acme, etc. The *buttress* thread usually has one surface normal to the axis of the screw—the other being inclined at 45° to it. It may thus be regarded as the first cousin of both square and vee threads. Fig. 93 indicates terms commonly used in regard to threads.

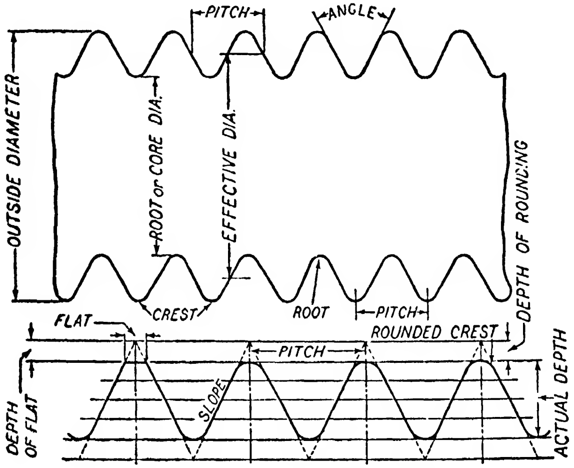


FIG. 93. USEFUL THREAD TERMS

Crest. The crest is the prominent part of the thread, whether of a male or female thread. It is the top surface joining the two sides of a thread.

Root. The root is the bottom portion of the valley of a thread, i.e. the bottom surface joining the sides of adjacent threads.

Angle of Thread. The angle of a thread is the angle between the sides or slopes, measured on an axial plane.

Actual Depth. The actual depth is half the difference between the outside- and core-diameters. It is the distance between the crest and the root measured radially, i.e. normal to the axis.

Pitch. In B.S. No. 84, 1940: the pitch of a thread is the distance measured parallel to its axis, between corresponding points on adjacent thread forms in the same axial plane.

(On single-start threads pitch = 1 ÷ no. of threads per inch. On vee threads it can be remembered as *a crest-to-crest measurement.*)

Lead. The lead of a screw thread is the distance it advances axially in one revolution.

Note. On a single-start thread the lead and pitch are identical. On a double-start thread the lead is twice the pitch; on a treble-start thread the lead is thrice the pitch, and so on.

The definitions of pitch and lead given above supersede the terms "divided pitch," etc., mentioned in previous impressions of this book. "Divided pitch" is a clumsy term which never commended itself to the trade. "Lead," on the other hand, is a term widely used in British and American practice.

Outside or Major Diameter. This is the largest diameter of a screw thread on a screw or nut, measured on a plane normal to the axis of the thread.

Effective or Pitch Diameter. On a single-start thread this is the length of a line lying in the plane of the axis of the screw measured between those points where it cuts the sides or slopes of the thread. It may also be described as the diameter of an imaginary cylinder which would pass through the threads at such points as to make the width of the thread and the width of the spaces between the threads at these points equal. (See Fig. 108.)

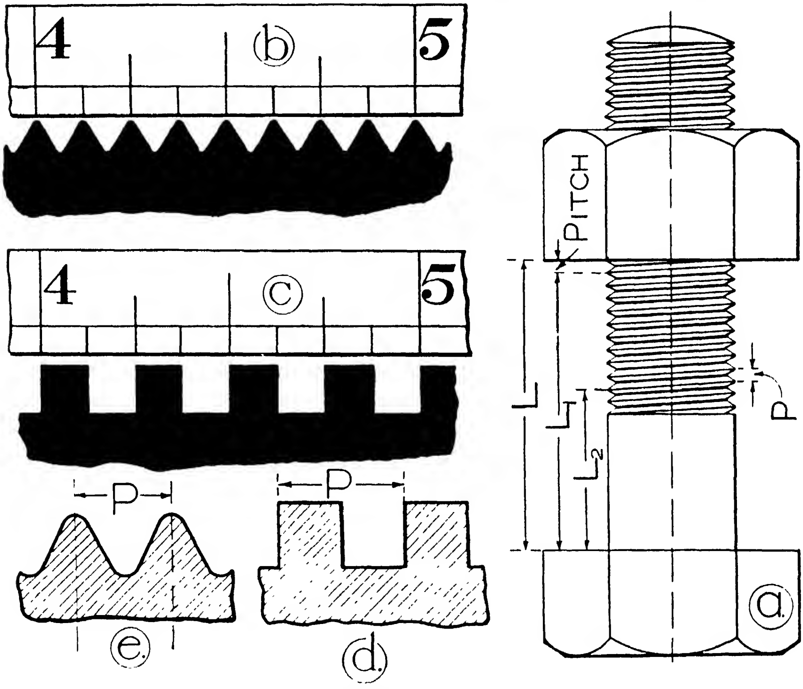


FIG. 94. SOME SINGLE-START THREADS

(a) Hexagonal-headed bolt and nut. If the nut is rotated once the difference between the measurements L and L_1 will equal pitch or lead. Suppose the nut is then rotated nine times exactly, distance L_2 should equal $L - 10 \times$ pitch of thread. Again, L_2 should equal $L_1 - 9 \times$ pitch of thread.
(b) Measuring the pitch of a vee thread. Pitch = ⅛ in. (to scale of rule shown).
(c) Measuring the pitch of a single-start square thread. Pitch = ¼ in.
(d) The pitch of a single-start square thread. (e) The pitch of a Whitworth thread.

Core, Root or Minor Diameter. This is the smallest diameter on the screw or nut. It is evidently the outside diameter minus twice the depth of the thread.

Compound, or Virtual, Effective Diameter. This is the effective diameter over a specified length of thread and is greater than the simple effective diameter by an amount due to the error in pitch.

Drunken Thread. A thread in which the advance of the helix is irregular in every convolution.

Flank or Slope. The surface of the thread which connects the crest with the root.

Helix Angle. The angle made by the helix of the thread with a plane perpendicular to the axis. The helix angle increases continuously from the crest to the root of the thread and is usually taken to mean the angle at the pitch diameter.

Flank Angles. The angles between the flanks of a thread and a plane perpendicular to the axis, measured in an axial plane.

Useful Notes for Inspectors.

1. Effective diameter = Outside or major diameter — depth of thread.

2. Core, root or minor diameter = Outside diameter — 2 (depth of thread).

3. Errors in pitch and angle in a male screw or gauge have the virtual effect of increasing its effective diameter. In a female screw (i.e. a nut) or gauge they virtually decrease its effective diameter.

SOME USEFUL THREAD PROPORTIONS

1. **Whitworth (B.S.W.)** (Fig. 95). This is the British Standard Whitworth. the first ever to be standardized and the most widely used of all British threads. d = actual depth = $0{\cdot}640327\,P$; Angle = 55°; D = angular depth = $0{\cdot}960495\,P$. P = pitch = $\dfrac{1}{\text{No. of t.p.i.}}$; r = radius of crest and root = $0{\cdot}137329\,P$.

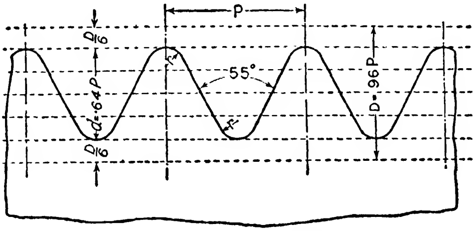


Fig. 95. Whitworth Thread Section

2. **British Standard Fine (B.S.F.).** The section of this thread is the same as the B.S.W. but finer pitches are tabulated. This enables small axial adjustments such as are commonly necessary on bolts for aero and automobile parts, etc. For B.S.F. bolts under 1 in. dia. $P = \dfrac{\sqrt{d^2}}{10}$, where d = full diameter of thread. For sizes between 1 in. and 6 in. $P = \dfrac{\sqrt[5]{d^5}}{10}$.

3. **British Standard Pipe (B.S.P.).** This also has exactly the same shape in section as the B.S.W. The tables, however, provide for much finer pitches in relation to diameter. Remember in connexion with external pipe threading that the diameter usually quoted is the *bore*, and not the outside diameter of the pipe. Thus the diameter of the external threading of a 2 in. nominal bore pipe is 2·35 in. whilst the core diameter is 2·23 in.

4. **British Association Thread (B.A.)** (Fig. 96). Used on small instrument work, etc. Recommended by B.S.I. for screws below ¼ in. diameter. The angle 47½°. The sizes are numbered 0 to 22, but in this country the sizes in most common use are 0, 2, 4, 6, 8 and 10. The larger the designating number the smaller the diameter of the thread.

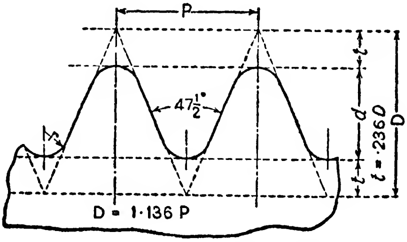


Fig. 96. B.A. Thread Section

P = pitch; D = angular depth = 1·136 P; d = actual depth = 0·6 × P; r = radius = $\frac{2 \times P}{11}$; Angle = 47½°; t = depth of rounding = 0·236 D.

Useful Summary (Fig. 97). (1) Whitworth, (2) U.S.A. Standard (Sellers), (3) B.A., (4) System International, (5) Cycle Engineers' Institute, (6) Acme, (7) Square, (8) Loewenherz. The *acme thread* is much more widely used nowadays because it is more readily *thread milled* than the square thread. Both are largely used for transmitting power and motion. The flat on the top of an acme thread = 0·3707 P; the flat on a square thread = ½P. For fuller descriptions of the various threads and comparisons between them, see the author's *Intermediate Engineering Drawing.*

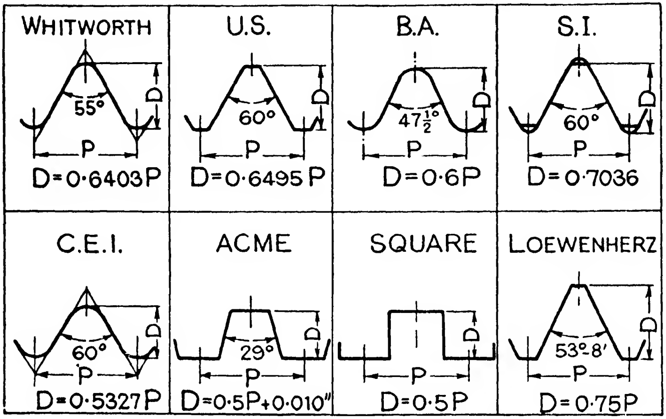


FIG. 97. VARIOUS THREAD SECTIONS

MEASURING THREADS

1. **Screw Pitch or Profile Gauge** (Fig. 98). This is used for rough ascertainment of the pitch of a screw.

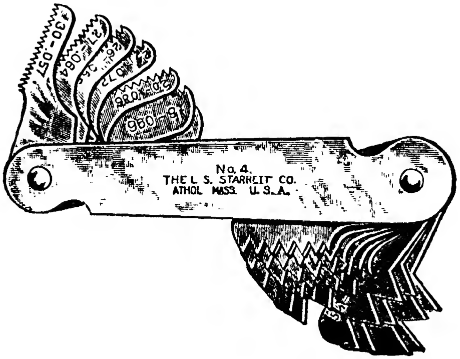


FIG. 98. PITCH OR PROFILE GAUGE FOR VEE THREADS

Description. It consists of two banks of profile gauges each including a number of threads of different pitch, but all of the same system, i.e. all applicable to Whitworth, B.A., U.S.A. Standard, etc. The end of each leaf is narrow to permit of passing it within a nut. When gauging a thread it should first be cleaned, held up to the light and the gauge placed upon it. If, as usually occurs, the thread has a regular standard pitch, one of the gauge leaves will correspond with its profile and the pitch can be read off from the surface of the leaf.

Measurement of Effective Diameter. The pitch-, effective-, or angle-diameter of a thread is very important, hence for taps, screw gauges, etc., this diameter is measured as well as the root—and outside—diameters. We do this by means of thread micrometers (Fig. 100), micrometers with special points (Fig. 101), or by a "wire method" (Figs. 102 to 106).

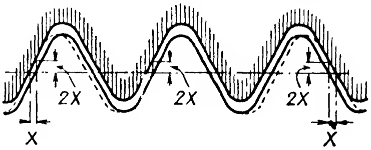


FIG. 99

Showing that the effective diameter of a screw is increased by approximately twice the amount of the pitch error

It will be clear that a cylinder of fixed diameter will always lie at a certain depth inside a thread groove. The "sides" of the thread should be "straight" in profile, i.e. tangential to both the root and tip arcs. Sometimes, however, outside and inside diameters are accurate but owing to a badly shaped thread profile the cylinder would lie nearer to, or farther from, the thread axis than it should. The use of wires, or small cylinders of correct and uniform dimensions, thus enables us to check the form of the thread by measuring its effective diameter. Errors in pitch also affect the effective diameter. (See Fig. 99.)

2. **Thread Micrometer** (Fig. 100). Where only a few threads are to be inspected at a time this micrometer measures pitch diameter and thickness of thread. The end of the movable spindle is conical but truncated, and the end of the anvil (fixed or movable) has the same angle as the thread to be measured. When the rounded or truncated conical end and the vee anvil are in contact, the zero line on the thimble represents a line drawn through the plane *CD*, so that readings are taken the same as in an ordinary micrometer. The reading indicates the *pitch diameter*, or the full diameter minus the depth of one thread.

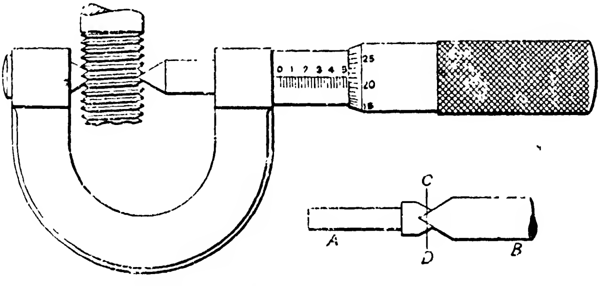


FIG. 100. THREAD MICROMETER FOR VEE THREADS

To find the theoretical pitch diameter we employ the formula, Pitch diameter = Outside diameter $-\dfrac{0{\cdot}640}{N}$. As an example the pitch diameter of a 1 in. diameter B.S.W. thread is 0.9200 in.

In measuring a small diameter thread with a large pitch the offset of the centre-lines of cone-pointed spindle and anvil necessary to take care of the helix angle of the thread is provided for by holding the anvil so that it is free to rotate, and by using various anvils for different pitches of threads.

3. **Micrometer with Ball Points** (Fig. 101). Screws may be measured by a standard micrometer fitted with different types of points. The micrometer can then be used by the inspector to *compare* the angle of the thread on the job with that on the thread of a standard gauge.

These points, typical of various forms in use, do not *directly* check the angle of a thread, but the angle may be checked by using different sizes of points, and *comparing* the size near the root of the thread with one type of ball, using a larger ball for the pitch diameter, and a still larger one near the top. If these three measurements agree with corresponding measurements on the standard gauge, the angle of the thread is correct.

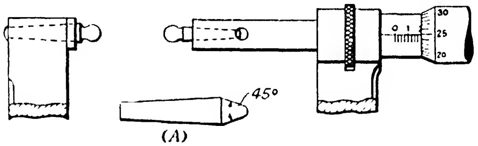
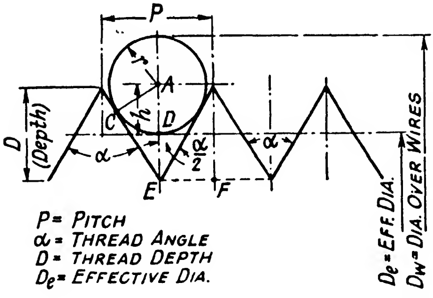


FIG. 101. BALL POINTS

MEASUREMENT OVER WIRES

The principles of measurement over wires can be shown by considering the general case, as illustrated in Fig. 101A, of a V-thread of angle α, depth D, pitch P, effective diameter D_e. Theoretically the exact diameter of the wire is not important provided that, in the three-wire system, all three wires are alike, and all protrude beyond the crests of the threads. In practice, however, it is found that *the best diameter wire* is one that touches the flanks of the thread at the effective diameter.



The point D is on the horizontal pitch line at some distance h from A. In this diagram the circle passes through D by chance. If radius r had been smaller the circle would have cut AE below D, if larger above it. Only in the particular case shown does $r = h$; it is usually less.

FIG. 101A

For B.S.W. threads the wires should not be smaller than 0·506 P nor larger than 0·853 P. A usual size is about two-thirds of pitch. The best diameter wire for B.S.W. threads is 0·56368 P. Wires must be lapped to within a ten-thousandth of an inch to true cylindrical shape.

See Fig. 101A. $AE = AC \operatorname{cosec} \frac{\alpha}{2} = r \operatorname{cosec} \frac{\alpha}{2}$

$$\begin{aligned}
D &= EF \cot \frac{\alpha}{2} = \frac{P}{2} \cot \frac{\alpha}{2} \\
DE &= \frac{D}{2} = \frac{P}{4} \cot \frac{\alpha}{2} \\
h &= AE - DE \\
&= \left(r \operatorname{cosec} \frac{\alpha}{2}\right) - \left(\frac{P}{4} \cot \frac{\alpha}{2}\right) \\
D_w &= D_e + 2h + 2r \\
&= D_e + 2\left\{\left(r \operatorname{cosec} \frac{\alpha}{2}\right) - \left(\frac{P}{4} \cot \frac{\alpha}{2}\right)\right\} + 2r \\
&= D_e + 2r\left(1 + \operatorname{cosec} \frac{\alpha}{2}\right) - \frac{P}{2} \cot \frac{\alpha}{2} \\
&= D_e + d_w\left(1 + \operatorname{cosec} \frac{\alpha}{2}\right) - \frac{P}{2} \cot \frac{\alpha}{2}
\end{aligned}$$

Assuming the use of three "best diameter" wires, touching the flanks of the threads at points separated by half the pitch,

$$\text{Wire dia. } (d_w) = \tfrac{1}{2} P \sec \frac{\alpha}{2}$$

If the screw is correct, dia. over wires,

$$D_w = D_e + d_w\left(1 + \sin \frac{\alpha}{2}\right)$$

For B.S.W. threads, D_e = Outside dia. of thread — 0·6403 P. As $\alpha = 55°$, $d_w = 0{\cdot}5637\ P$, and D_w = Outside dia. of thread + 0·1832 P.

Testing Angle of Thread by Wires. The three-wire system is employed, using two sets of wires of different diameter, so that wires touch the flanks of the threads at different distances (as widely separated as possible) from its axis. Obviously if the wire is too small it will rest on the valley radius, if too large it will not touch the flanks but will rest on the radii of the crests. For B.S.W. threads it is well to know the limiting diameters for the wires. They are as follows:

Smallest wire dia. = 0·506 × P; largest wire dia. = 0·853 × P. If the screw is correct, $D_w = D_e + d_w\,(1 + \operatorname{cosec} \alpha) - \frac{1}{2}P \cot \alpha/2$.

This formula may be applied whatever the effective dia., pitch, thread angle, wire dia. (within the limits previously mentioned).

The checking of thread forms by means of optical projection is referred to elsewhere in this book. Thread angles can also be tested under a toolmaker's microscope.

1. **One-wire System** (Fig. 102). To measure *pitch* or *effective* diameter we can use an ordinary micrometer and one wire. The micrometer must be held at right-angles to the axis of the work.

If D is the micrometer reading over the wire when pitch diameter is correct the formula for a Whitworth thread is—

$$D = 1{\cdot}583 \times \text{diameter of wire} - \frac{0{\cdot}8004}{\text{No. of t.p.i.}} + \text{nominal outside diameter}$$

If the screw is oversize, one-half of the amount it is oversize must be added to D. Similarly, if the screw is undersize, one-half of the amount it is undersize must be subtracted from D. This method of measuring is not so popular as the three-wire method, but is convenient for coarse pitch threads. When producing cut threads on a screw gauge the first element checked by the operator is the effective diameter, which is readily checked by the one-wire system. Before finally passing for size the inspector usually employs the three-wire system which certifies the squareness of the micrometer reading in relation to the axis of the gauge.

2. **Three-wire System** (Fig. 103). Two wires of known diameter

are placed in contact with the sides of the thread on one side and one, coming immediately between them, on the other. A micrometric

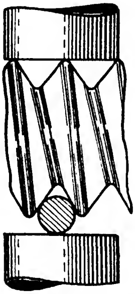


FIG. 102. ONE-WIRE MEASUREMENT

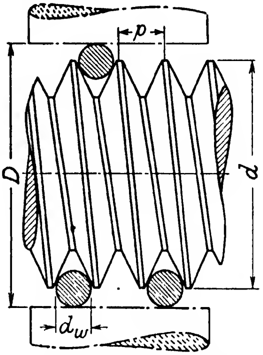


FIG. 103 THREE-WIRE MEASUREMENT

measurement is taken over the wires and a calculation made with a formula that varies with different sections or systems of threads.

In Fig. 103 D is the outside diameter over the wires,
d ,, ,, diameter over the tops of the threads,
p ,, ,, pitch of the thread,
d_w ,, diameter of the wires.

Then $D = d - Ap + Bd_w$
For B.S.W. threads $A = 1{\cdot}6008$, $B = 3{\cdot}1657$.
,, U.S. ,, $A = 1{\cdot}5156$, $B = 3{\cdot}0000$.
,, B.A. ,, $A = 1{\cdot}7363$, $B = 3{\cdot}4829$.

See the N.P.L. "*Notes on Screw Gauges*"

For B.S.W. threads the wires must not be smaller than $0{\cdot}506p$ nor larger than $0{\cdot}853p$. A usual size is about two-thirds of pitch. The "best diameter" wire is one that contacts at the pitch line or mid slope of the thread. Its diameter equals $0{\cdot}56368p$. (See Fig. 104.)

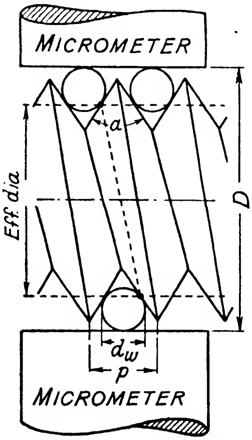


FIG. 104. THE "BEST DIAMETER" WIRE

$$\text{Effective diameter} = D + \frac{p}{2\tan\frac{a}{2}} - d_w - \frac{d_w}{\sin\frac{a}{2}} - C$$

where C is a correction term for compensating the obliquity of the wires in the thread. For Whitworth threads the value of C is usually of the order of 1/10 000 in. to 2/10 000 in.

For such accurate readings special charts and tables have been prepared by the Société Genèvoise d'Instruments et Physique, Geneva. For those who wish to study the mathematical formulae and charts used for the wire method of screw thread gauging, reference should be made to an informative article published in *Machinery*, 20th October, 1938.

Comparison of Figs. 103 and 102 will show that the three-wire method has an advantage over the one-wire method in that the accuracy of the outside diameter of the thread need not affect the measurement across the wires.

It is always awkward to hold by hand three

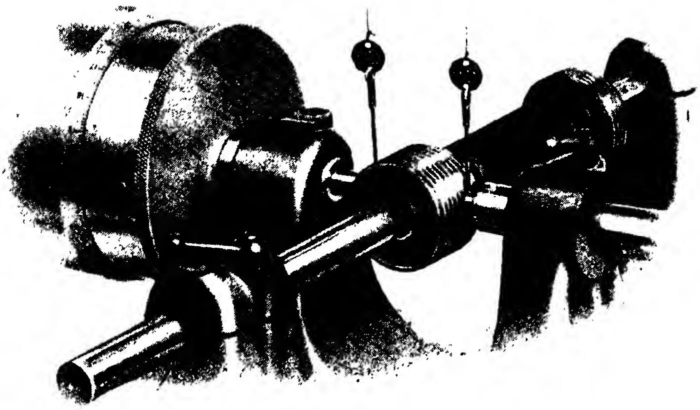


FIG. 105. P.V.E. DIAMETER-MEASURING MACHINE
(*By courtesy of the Makers*)

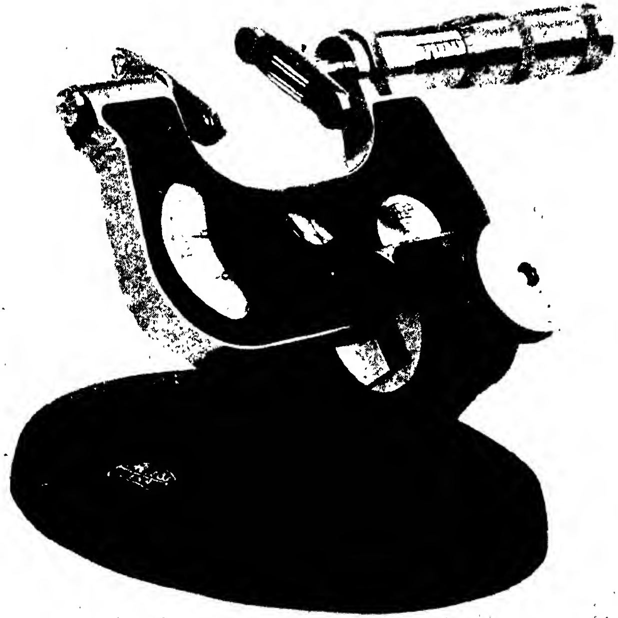


FIG. 106. THE ZEISS MICROMETER
(*By courtesy of Alfred Herbert Ltd.*)

separate wires in the thread grooves. For fine pitches a tool turner or inspector may find it practicable to use a single length of flexible wire which can be wrapped round the thread. Special stands have therefore been designed to hold two wires, by means of magnets. The upper wire can then be held and the micrometer adjusted. The lower part of the stand serves as the anvil of the micrometer and an arm, adjustable on a vertical pillar, serves to carry the moving spindle and head of the "mic."

P.V.E. DIAMETER-MEASURING MACHINE (Fig. 105). This interesting illustration shows a close-up view of the measurement of a screw plug gauge on a P.V.E. Diameter-measuring Machine (also referred to on page 79) with the aid of thread measuring cylinders, rods, or wires.

THE ZEISS MICROMETER (Fig. 106). It will be seen that wires are mounted so that they can easily be fitted to the anvils of a micrometer. For medium-sized threads the three wires are mounted on two frames which can be carried on the anvils of the micrometer. The wires are held loosely on the frames so that they will adapt themselves to position in the thread grooves. The wires in a set are interchangeable. For measuring coarse pitch threads the pair of wires in the frame is backed by a gauge block which makes contact with the micrometer anvil. No calculations are necessary. Thus there is economy of time. Tables are supplied for each thread standard, giving thread diameter, number of t.p.i., wire diameter, and the reading the instrument should register. Any deviation indicates a deviation from accuracy in effective diameter.

GAUGES FOR THREADED HOLES. In Fig. 107 (*a*) is shown (at the left-hand end) a typical "go" full form screw plug gauge made very accurately to conform closely to the perfect size and shape of the thread being inspected. Generally the effective diameter is made to minimum tolerance, so that the gauge should, in general, enter the work quite freely.

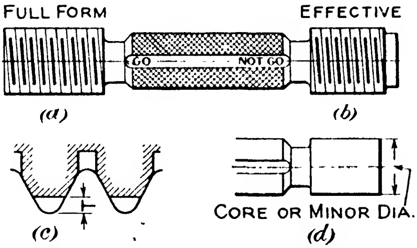


Fig. 107. Gauges for Screw Threads

At the right-hand end, i.e. at (*b*), a "not go" effective gauge is shown, having its effective diameter made to the maximum tolerance. On the "not go" end the threads are "truncated," or "cleared away," at both crest and root, so that contact can only take place on the flanks of the threads. (See Fig. 107 (*c*).) The **Air Ministry** have adopted a truncation table giving values of T, and this is consulted when designing modern "not go" effective diameter gauges for threads of Whitworth and B.A. forms. Slight "interference" is inherent in the design and size and therefore the gauge should *not* enter the hole being inspected.

At Fig. 107 (*d*) is a plain plug which may be the maximum, or "not go" size of the core, or minor diameter, or may be the minimum or "go" size, according to requirement.

Inside threads are sometimes examined with regard to angle and form through the medium of a cast of the thread either in plaster of Paris or dental wax. Plaster is commonly used for holes of ½-in. diameter or over, and a dental wax which softens in hot water is used for smaller sizes.

Inspecting Tapped Holes. This may be done on the site of manufacture by first inspecting the tap especially as to angle and pitch diameter. The tapped holes can then be viewed from time to time with "go" and "not go" gauges. Checking against wear of the tap may be done by testing the tapped holes with a "go" gauge. It may be preferred to check tapped holes by using a "go" *thread plug gauge,* and "not go" *thread plug gauge* for the core diameter.

Alternatively before putting a tap into use it may be used to tap a trial hole. The core diameter of this tapped hole can then be checked with a "go" and "not go" *cylindrical plug gauge,* and the screw thread by "go" and "not go" *screw plug gauge.*

Inspecting Screwed Parts with Protective Coatings.* Especially in the aero industry many parts are given protective coatings which increases their thickness by about 0·0003 in. in the case of cadmium plating and about 0·00125 in. in the case of cosletizing. Screwed studs and nuts so treated are sometimes checked before treatment by means of inspection gauges set 0·001 in. *under* the low limit on effective diameter for studs, and from 0·001 in. to 0·002 in. *above* the high limit on effective diameter for nuts.

Screw Thread Gauge Tolerances. For interchangeability of threaded work the following must be controlled within specified limits: outside diameter, core diameter, angle, pitch, simple effective diameter, and compound effective diameter.

The outside and core diameters are usually not important so long as the maximum limits are not exceeded. The most important measurement is the *simple effective* diameter or the *pitch* diameter. (See Fig. 108.) The more accurate the pitch and angle the more nearly will the effective diameter approach its nominal size.

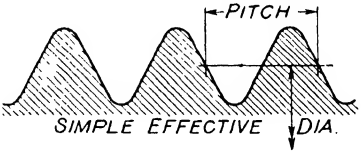


FIG. 108. SIMPLE EFFECTIVE DIAMETER, OR PITCH DIAMETER

Tolerances are placed on the effective diameter and in this connexion it should be mentioned that the tolerance on the screwed hole should be identical with that on the screw, the only allowance required being a slight clearance between the largest screw and the smallest screwed hole. This avoids interference.

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* SHERARDIZING. This is a method for protecting the surfaces of easily corrodible steel parts by applying a coating of a less corrodible material, viz. zinc. The pieces are heated at a relatively low temperature in contact with zinc dust; considerable alloying takes place although a thickness of only 0·0005 in. or so remains on the surface. D.T.D. Spec. No. 908 applies.

COSLETIZING. This is a protective process for coating iron and steel parts to resist corrosion and rusting. The method resembles Parkerizing except that the bath includes zinc phosphate and phosphoric acid.

PARKERIZING. This, too, is a coating process to guard against corrosion and rusting. The surfaces of the parts are first cleaned by sandblasting, after which they are immersed up to three hours in a boiling acid solution containing iron phosphate.

The N.P.L. has drawn up a specification of limits on the three diameters for screw gauges in three classes, viz. reference, workshop, and inspection. See "Notes on Screw Gauges," published by H.M. Stationery Office, Kingsway, London, W.C.2, also B.S. No. 919, described on page 132.

Fig. 109 Ring Screw Gauge

NORMAL RING SCREW GAUGE (Fig. 109). This is a *Matrix* normal ring gauge made to nominal size or N.P.L. inspection or workshop limits.

In general it may be said that ring screw gauges are admirably suited for checking concentricity of external threaded parts. For testing elements intimately concerned with the mechanical strength of the screw, the caliper gauges are best. (See additional note on page 132).

CALIPER GAUGES FOR SCREW THREADS. Figs. 110 and 111 show a Wickman type of adjustable caliper thread gauge.

Description. The frame is of hard cast iron designed for lightness and rigidity. The hardened tool steel anvils, which have a "chaser-like" appearance, are a sliding fit in the holes—the latter being bored, ground, and lapped in the frame, thus securing rigidity. Hardened abutments solidly fixed to the frame prevent the anvils turning or tilting. Each pair of anvils may be adjusted to within 0·0001 in. to a setting piece (usually a screw plug gauge), the adjusting arrangements being simple, ingenious, and efficient. To prevent the setting being interfered with, a monogrammed lead seal is fixed by means of a special sealing press over the ends of the adjusting screws.

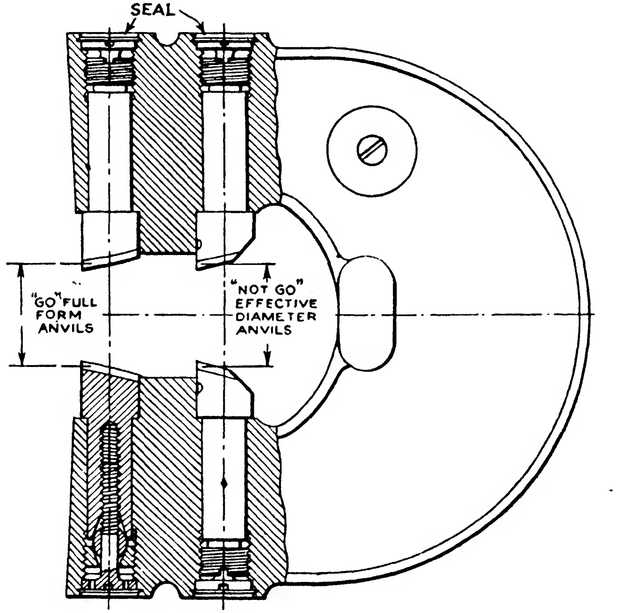


Fig. 110. Adjustable Caliper Thread Gauge of Wickman Type

Principle. We have already seen that it is necessary when aiming at interchangeable threaded work of good quality and sound mechanical strength to provide means to control the three main elements, viz. major, minor, and effective diameters. In view of the accuracy to which modern screwing tackle is made, the major and minor diameters will bear reasonable relation to the simple effective diameter, and it is therefore only necessary to ensure that they are not too large. Then, too, the virtual effective diameter must also not be too large. Therefore the **front, or "go," anvils** are provided with a full form of thread, are of sufficient width to cover the engagement of the screw, and are set to nominal diameter. The **rear anvils** have truncated threads in order that contact is made only on the central portion of the flanks of the thread and that no effects of pitch error are taken into account.

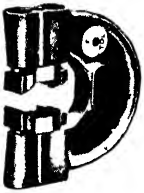


FIG. 111. WICKMAN ADJUSTABLE-LIMIT SCREW GAUGE

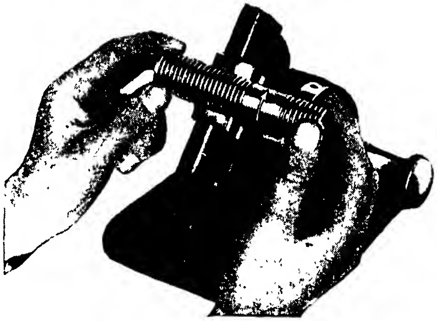


FIG. 112. STAND FOR HOLDING WICKMAN CALIPER GAUGES

Thus, in brief, the front anvils of the gauge ensure that no element of the thread is oversize, and the rear anvils that the simple effective diameter is not undersize. The threads on the anvils are relieved in order that there is no interference with the helix of the thread being inspected. In this way inspection takes place purely on an axial plane of the thread, at which place the true thread form is located. Since there is no interference with the helix angle, the same gauge may be used for both right and left threads.

In use the work should be passed, mainly under its own weight, from the front to the back of the anvils. It should on no account be forced, especially through the "go" anvils.

GAUGES WITH ROLLER TYPE ANVILS. There are a number of these on the market similar in general principle to the Wickman Gauge previously described, but having roller type anvils. Two well-known makes are the Newall and the Matrix. We shall in the following notes describe very briefly the *Matrix Roller Type Adjustable Limit Thread Gauge* as made by the Coventry Gauge & Tool Co. Ltd. (See Fig. 113.)

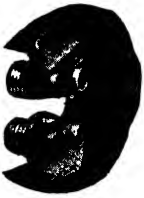


FIG. 113. ADJUSTABLE-LIMIT THREAD GAUGE, MATRIX ROLLER TYPE

Description. The gauge consists essentially of a frame and a pair of rollers. The frame is made of hard cast iron and has proportions ensuring rigidity and permanence of dimensions. At the front is a pair of full form "go" rollers; at the back is a pair of "not go" rollers, the threads of the latter being truncated at both crest and root so that contact is made only on the flank of the thread.

The rollers are of annular thread form, corrected to compensate for helix angle interference. They are mounted on eccentric studs locked in position to the frame, a circlip retaining them on the studs without preventing their free rotation. The tolerances are such that the circlip cannot be removed unless the setting is disturbed. The gauges are very easily adjusted. The locknut is slackened and the stud rotated by means of a screwdriver or special adjusting key until the eccentric gives the setting required as determined by the double-ended setting plug. They are then secured by tightening up the locknut with the special adjusting key. Unauthorized interference with the setting is guarded against by pressing a lead seal into the recess provided in the nut.

FIG. 114. DOUBLE-ENDED SETTING PLUG

The makers recommend that for setting the gauges to give the desired tolerances between the "go" and "not go" rollers a double-ended setting plug be used. (See Fig. 114.) As the crests and roots are removed, only the effective diameter is used in setting the rollers. The plug is arranged to set the "go" rollers to nominal size, and the "not go" to the nominal size minus the tolerance intended. Various standards of tolerances are in use, among them is the Herbert Standard as given in the booklet, "An Efficient Gauging System," and the Wickman Thread Caliper Gauge Catalogue, G7.

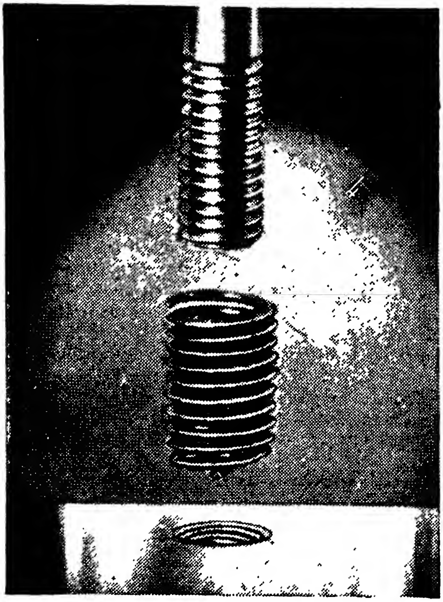


FIG. 115. THE SCREW, BUSHING (THREAD INSERT), AND TAPPED HOLE

Aero Threads (Figs. 115–117). The reader will be aware that on machine parts subject to vibration it is essential to provide means for locking nuts. Space forbids discussion of locking arrangements in this short book, but many examples will be found in the various engineering drawing books by the present author.

In all high-speed engines, and especially in aero engines, many of the parts are subjected to heavy vibration and repeated stresses. As a consequence failures have occurred due to low fatigue capacity and poor shock resistance. It is a common cause of fatigue failure to leave sharp inside corners, grooves, etc. Thus threads of the U.S. 60° form have failed on account of the concentration of stress at the sharply cornered roots. To some extent this trouble is reduced in threads of Whitworth form which have filleted roots. Recent tests having shown that the endurance limit of U.S. threads is less than that of Whitworth threads, much interest is being shown in the *aero thread system* in which the male threaded piece, e.g. stud, screw, etc., has a shallow depth and well-rounded root. It is used in conjunction with a spiral bushing.

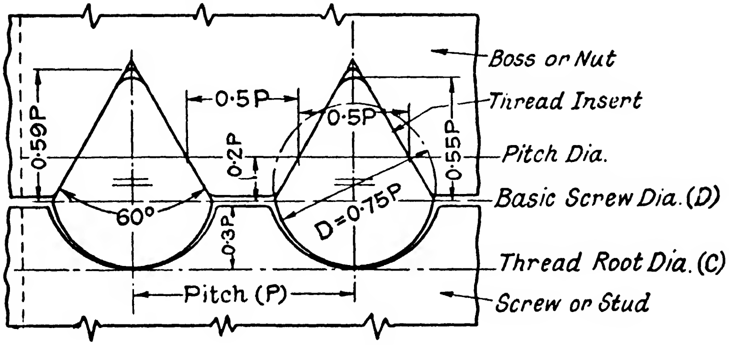


FIG. 116. SECTIONAL ASSEMBLY OF NUT, SCREW, AND THREAD INSERT

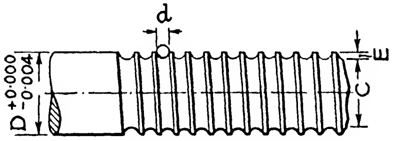


FIG. 117. THE SCREW OR STUD

In Fig. 115 is shown the screw, bushing, and tapped hole of such an assembly, the block being reproduced by courtesy of F. J. Camm, Esq., Editor of *Practical Engineering*. The bushing, or insert, is spirally wound, of high tensile stainless steel or bronze spring wire, and fits the previously tapped hole. The latter has a coarse pitch vee-thread somewhat like the American National Coarse Thread. The assembly is so designed that although the bushing can readily be screwed into position, once inserted it becomes to all intents and purposes a fixture in the tapped hole. The male screw component has the new thread form, the groove being shallow and having a well-rounded root to accommodate the similarly shaped insert or bushing. This liberal filleting tends to obviate the incidence of heat treatment cracks which often occur at sharper roots.

An added advantage attaching to this system is that it permits the use of screws and removable screw fastenings in the light alloys of aluminium or magnesium, as the bushing fully protects the soft threads in the tapped hole, and its anti-frictional property allows smooth non-wearing engagement of the set-screw. Where maximum tensile strength is required, however, aero thread set-screws made of heat-treated alloy steel are used.

MEASURING PITCH. We have seen that errors in pitch increase the effective diameter of a screw. Tolerances are placed on this diameter because it is one of the determining factors in the mechanical strength of a screw—another being the area of flank contact. As most modern screwing tackle is so accurately made, the gauges for routine inspection of mass-produced interchangeable threaded pieces are normally designed to control, within the predetermined limits, the three elements: major, minor, and simple effective diameters. Measurement of pitch is mainly necessary in the tool-room or Inspection Department when checking taps, and similar threading tools, screw gauges, etc.

Of course the projection method of comparing the form of the thread with that of an accurately made thread profile diagram is useful. In the direct measurement of pitch various devices are employed, in most cases carrying an indicator attachment.

P.V.E. SCREW PITCH MEASURING MACHINE (Fig. 118). A brief description is given of this well-known machine designed by the N.P.L. and made by the Pitter Gauge and Precision Tool Co. Ltd. with the permission of the laboratory.

The screw being measured is held between the centres. The indicator, carrying a stylus bearing on the flanks of each thread successively, is carried on a slide mounted on balls. This slide is actuated by means of the special micrometer shown at the right. The act of rotating the micrometer spindle causes the slide to move in relation to the fixed centres, or in other words causes the indicator to move in relation to the gauge. The stylus, which is mounted on a leaf spring, falls in and out of each thread. The point of the indicator reads zero when this stylus is in a central position in each successive thread. The micrometer reading is taken each time the indicator reads zero. These readings therefore show the pitch error of each thread of the screw being measured. Special discs are provided to fit the micrometer to suit all common pitches. Any other pitch can be measured by means of a fully graduated disc and special tables provided with the machine.

The small handwheel shown beneath the micrometer actuates a screw for the purpose of moving the indicator in relation to the slide so as to bring the stylus opposite to the screw to be tested in any position between the centres. The travel of the micrometer is 1 in. For measuring the pitch of screw ring gauges an internal attachment is fitted in front of the indicator.

RECENT THREAD SPECIFICATIONS

(1) **B.A. Screw Threads** (War Emergency Revision of B.S. No. 93–1919). The complete revision of B.S. No. 93 has been deferred until after the war but a War Emergency Slip CF (ME) 6521, forming an addition to B.S. No. 93 has been issued. The main feature of the proposed revision of B.S. No. 93, viz. a considerable increase in the tolerance allowed on the minor (core) diameters of nuts and internal threads has been covered by the War Emergency Revision so as to facilitate production. The tolerances now recognized for the minor diameters are equal to 0·35 times the pitch. These are given, together with upper and lower limits, in the tables. These minor diameter tolerances are such as to permit of a tapping drill being used of ample size to prevent binding at the

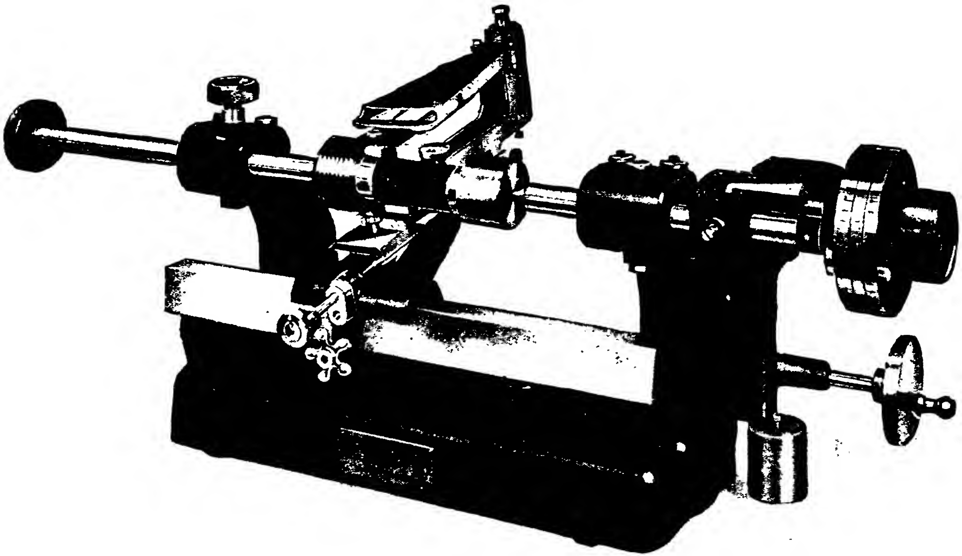


Fig. 118. P.V.E. Screw Pitch Measuring Machine

A test on a screw pitch measuring machine is more dependable than the method in which pitch is found by measuring the displacement of a nut per revolution of the screw. Periodic errors which occur during the length of the nut do not affect the extent of its displacement and thus do not reveal themselves. However, the method does give the effective pitch of the combined screw and nut, which for many purposes is all that is required.

(*By courtesy of the Pitter Gauge and Precision Tool Co. Ltd.*)

root of the tap. It will be understood that if full advantage is taken of these generous tolerances on the minor diameters of internal threads, the crests of such threads will be flat. This follows both general engineering practice and that of certain firms who use a modified form of thread with flat crests with the object of providing ample clearance at the crests and roots of their mating threads. It is recommended that B.A. nuts and tapped holes made to these increased tolerances on the minor diameter should be controlled with "not go" effective screw gauges, as well as "not go" plain gauges for the minor diameter, and full form "go" plug screw gauges.

(2) **Screw Thread Gauge Tolerances** (B.S. No. 919). This is a War Emergency Specification for Screw Thread Gauge Tolerances suitable for controlling screw threads covered in B.S. No. 84–1940 (Screw Threads of Whitworth Form). It relates solely to the tolerances on the gauges and does not deal otherwise with the design or dimensions of the gauges themselves. The principal object of the specification is to make some adjustment of the tables published by the National Physical Laboratory. Extra latitude is allowed in the tolerances on the gauges so as to facilitate their manufacture, whilst at the same time gauge makers will be enabled to keep the effective diameter high and thus increase the useful life of the gauges. This adjustment applies to "go" plug screw gauges. B.S. No. 919 gives appropriate tolerances for plug, ring and caliper gauges for threads of Whitworth and metric form in diameters up to 6 in., and for B.A. threads down to No. 7.

Notes On Screw Gauges (new edition). Prepared by the National Physical Laboratory and published by H.M. Stationery Office, Kingsway, W.C.2. Covers modern thread cutting and thread measurement very ably.

Additional Note on Ring Screw Gauges Used for Concentricity Testing. On page 126 mention is made of the fact that Ring Screw Gauges are admirably suited for checking concentricity of external threaded parts. Adjacent to the notes is an illustration of a *Simple Ring Screw Gauge* (Fig. 109). Concentricity could not be decided by means of the simple ring gauge shown, for it has a full thread completely through it. Ring gauges, of course, can only check concentricity provided that male or female registers are incorporated in such gauges.

CHAPTER XI

MEASURING GEARS AND ANGLES

TOOTHED GEARING. The subject of gearing is one of the most interesting branches of engineering, but as finality in efficient gear design has not yet been attained it is proposed merely to describe fundamental commonly accepted terms and straightforward methods of measurement of simple forms of toothed gears. Inspectors specially concerned with gears should obtain the various current B.S. Specifications.

The great advantage of toothed gears over friction drives lies in their ability to transmit considerable power *positively*, i.e. without slip.

SPUR WHEELS. These are used to connect *parallel shafts lying in the same plane.* If the shafts shown in Fig. 119 are to rotate in opposite directions, any desired speed ratio can be obtained by connecting them by two cylinders arranged to transmit motion by friction. These cylinders will touch along a line *PP* parallel to the axes *CD* and *EF*. If no slip occurred the cylinders would have the same surface velocity. However, in practice, a certain amount of slip is bound to ensue and therefore the surfaces of the cylinders are generally provided with teeth, these being formed partly above and partly below the **pitch surfaces,** i.e. the outer surfaces of the two smooth cylinders which would be employed for a corresponding friction drive.

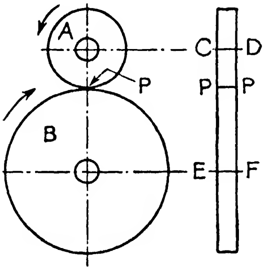


FIG. 119. PITCH SURFACES OF SPUR WHEELS

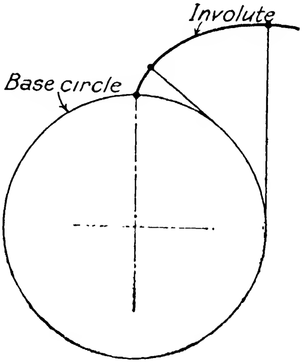


FIG. 120. THE INVOLUTE OF THE BASE CIRCLE

Form of Teeth. The great majority of modern toothed gears have teeth of **involute** form, the curves of the teeth profiles being parts of a curve known as the involute of a circle. In Fig. 120 is shown a circle representing a cylinder round which an inextensible string is wrapped. If one end of the string is unwound, being kept taut meanwhile, it traces out a curve termed the involute of the circle. This circle is termed the **base circle** of the involute.

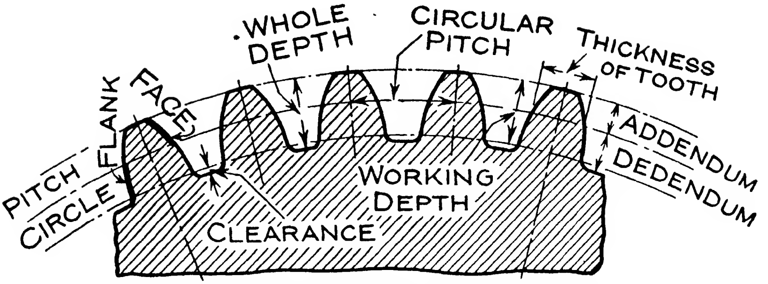


FIG. 121. TERMS USED IN CONNEXION WITH SPUR GEARING

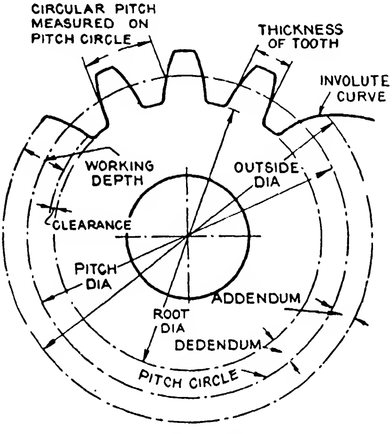


FIG. 122

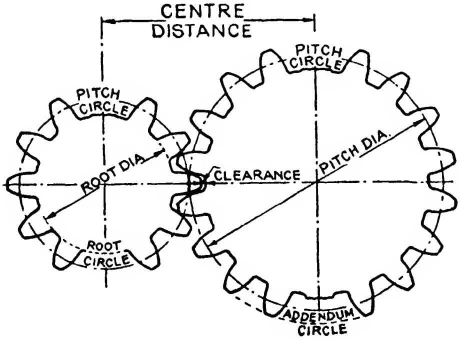


FIG. 123. TOOTHED GEARING TERMS

TERMS USED IN INVOLUTE GEARING. (See Figs. 121 to 123.)

The Addendum is the height from the pitch circle to the tip of the tooth.

The Dedendum is the depth of tooth space below the pitch circle.

The Pitch Circles of a pair of gears are those circles coaxial with the gears, and in peripheral contact, which will roll together without slip. The pitch circles are the outlines of the imaginary smooth rollers or friction discs. Many important measurements are taken on and from these circles.

The Pitch Diameter of a gear is the diameter of its pitch circle.

The Root Diameter of a gear is the diameter at the bottom of the tooth spaces.

The Circular Pitch (p) is the distance from a point on one tooth to a corresponding point on the next, measured round the pitch circle.

The Diametral Pitch (P) is the number of teeth divided by the pitch diameter.

The Module (m) is the pitch diameter divided by the number of teeth. It is the reciprocal of diametral pitch. Whilst the module may be expressed in any units, when no units are stated it is assumed to be in millimetres.

The Tooth Thickness is the length of arc of the pitch circle between opposite faces of the same tooth.

The Chordal Thickness of a tooth is the length of the chord subtended by the tooth thickness arc.

The Clearance is the shortest distance between the top of a tooth and the bottom of its mating space.

The Base Circle Diameter is the diameter of the circle from which the involute is generated.

The Line of Action is the common tangent to the two base circles which passes through the pitch point of a pair of mating gears.

The Path of Contact is that portion of the line of action on which tooth contact takes place.

The Pressure Angle is the acute angle formed between the line of action and the common tangent to the two pitch circles which passes through the pitch point.

The Fillet is the rounded corner at the bottom of the tooth space.

Arc of Approach is the arc of the pitch circle through which a tooth travels from the time it is in contact with a mating tooth until it is in contact at the line of centres.

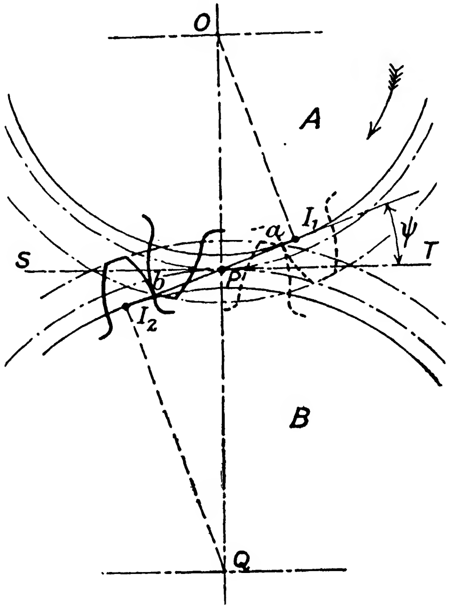


FIG. 124. THE PRESSURE ANGLE AND PATH OF CONTACT

Arc of Recession is the arc of the pitch circle through which a tooth travels from the time it is in contact with a mating tooth at the line of centres until contact ceases.

Backlash is the shortest distance between non-driving surfaces of adjacent teeth in mating gears.

The Pressure Angle and Path of Contact More Fully Explained. If two gears, each having teeth with involute profiles, are meshed together as in Fig. 124, the common normal to the teeth at any point at which contact occurs is tangential to each of the base circles. This contact always takes place along a straight line I_1PI_2, termed the "path of contact." The path of contact passes through the pitch point (see P in Fig. 124) and is inclined at an angle ψ, termed the "pressure angle," to the common tangent SPT to the pitch circles. The path of contact cannot extend beyond the points I_1 and I_2, where it is a tangent to the respective base circles.

The standard pressure angle recommended by the B.S.I. is 20°. See Fig. 125, which is reproduced from *A First Year Engineering Drawing* by the same author, and is one of a series of instructive, carefully explained drawing exercises in connexion with gearing.

Diameter of base circle = pitch diameter × cosine of pressure angle.

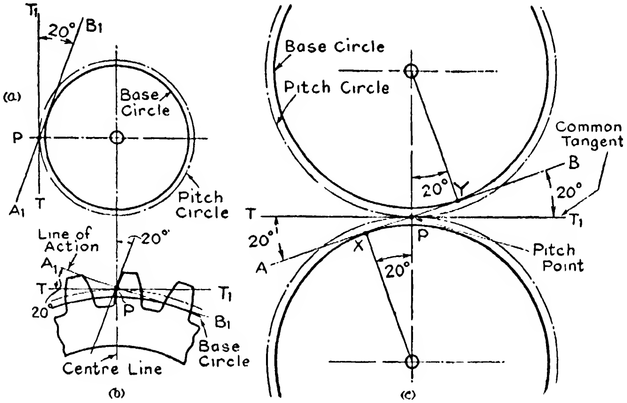


FIG. 125. ILLUSTRATING THE RELATIONSHIP BETWEEN THE PATH OF CONTACT, THE PRESSURE ANGLE, AND THE BASE CIRCLE

USEFUL SUMMARY

	Cast Gears	Machine-cut Gears (14½°)	B.S.I. Standard (20°)
Addendum . .	$0{\cdot}3p$	$0{\cdot}318p$	$0{\cdot}3183p$
Dedendum . .	$0{\cdot}4p$	$0{\cdot}368p$	$0{\cdot}3979p$–$0{\cdot}4583p$
Tooth Thickness .	$0{\cdot}48p$	$0{\cdot}5p$	$0{\cdot}5p$
Space Width . .	$0{\cdot}52p$	$0{\cdot}5p$	$0{\cdot}5p$

$$\text{Circular pitch } (p) = \frac{\text{Pitch diameter} \times \pi}{\text{No. of teeth}}$$

$$\text{Diametral pitch } (P) = \frac{\text{No. of teeth}}{\text{Pitch circle diameter}}$$

$$\left.\begin{aligned} \text{Circular pitch} &= \frac{\pi}{\text{Diametral pitch}} \\ \text{Diametral pitch} &= \frac{\pi}{\text{Circular pitch}} \end{aligned}\right\} \therefore \text{Circular pitch} \times \text{Diametral pitch} = \pi$$

SIMPLE SPUR-WHEEL FORMULAE

(For simplicity in the following formulae we use the contractions C.P. and D.P. for circular and diametral pitch respectively.)

(*a*) Circular Pitch

$$\text{Circular pitch (C.P.)} = \frac{\text{Circumference of pitch circle}}{\text{No. of teeth}}$$

$$\text{Diameter of pitch circle} = \frac{\text{No. of teeth} \times \text{Circular pitch}}{\pi}$$

$$\text{No. of teeth} = \frac{\text{Circumference of pitch circle}}{\text{C.P.}}$$

$$\text{Outside diameter} = \frac{(\text{No. of teeth} + 2) \times \text{C.P.}}{\pi}$$

$$\text{Centre distance apart} = \frac{\text{Pitch diameter of wheel} + \text{Pitch diameter of pinion}}{2}$$

$$\text{Corresponding diametral pitch} = \frac{\pi}{\text{C.P.}}$$

(*b*) Diametral Pitch.

$$\text{Diametral pitch (D.P.)} = \frac{\text{No. of teeth}}{\text{Diameter of pitch circle}}$$

$$\text{Pitch circle diameter} = \frac{\text{No. of teeth}}{\text{D.P.}}$$

$$\text{No. of teeth} = \text{D.P.} \times \text{Diameter of pitch circle}$$

$$\text{Outside diameter} = \frac{\text{No. of teeth} + 2}{\text{D.P.}}$$

$$\text{Centre distance apart} = \frac{\text{No. of teeth in gear} + \text{No. of teeth in pinion}}{\text{Twice D.P.}}$$

$$\text{Corresponding circular pitch} = \frac{\pi}{\text{D.P.}}$$

SPUR-WHEEL EXAMPLE. 60 teeth, 5 D.P. (*Note.* 5 D.P. = 5 diametral pitch, but 5 in. pitch means 5 in. circular pitch.) Involute full depth teeth. *Corresponding circular pitch* = 0·628 in. C.P.

Pitch circle diameter—(*a*) $\frac{\text{No. of teeth} \times \text{C.P.}}{\pi} = \frac{60 \times 0{\cdot}628}{3{\cdot}1416} = 12 \text{ in.}$

(*b*) $\frac{\text{No. of teeth}}{\text{D.P.}} = \frac{60}{5} = 12 \text{ in.}$

Outside diameter—(*a*) $\frac{(\text{No. of teeth} + 2) \times \text{C.P.}}{\pi} = \frac{62 \times 0{\cdot}628}{\pi} = 12{\cdot}4 \text{ in.}$

(*b*) $\frac{\text{No. of teeth} + 2}{\text{D.P.}} = \frac{62}{5} = 12{\cdot}4 \text{ in.}$

Outside Diameters. The outside diameter is found by adding twice the addendum to the pitch diameter. It should be mentioned that whilst in the past the addendum was often made equal to the module it is nowadays more common, in order to avoid weak and inefficient tooth shapes, to vary the size of the addendum according to the numbers of teeth in the mating gears. Too large an addendum produces pointed teeth; too large a dedendum produces "undercut" teeth with weak roots. Most modern teeth have a total depth equal to 0·716 times the pitch. Addenda vary greatly.

The Involute Rack. When a wheel with few teeth gears with another of larger size we call the smaller a pinion. Imagine the diameter of the larger wheel to increase gradually so that the difference between circular and chordal pitches becomes progressively less and less. If the diameter of the pitch circle of the wheel be ultimately increased to infinity, the circumference of the pitch circle will become a straight line, i.e. the pitch surface of the wheel will become a plane, whilst circular and chordal pitches will be the same. We shall then have a *rack*, which is sometimes referred to as *a spur wheel of infinite diameter.* The pitch line of the rack may be represented by a straight line tangential to the pitch circle of the pinion. How does this affect the involute system? The involute of a base circle of infinite diameter is a straight line, so that the sides of the teeth of an involute rack gearing with an involute pinion may be shown as straight lines, at an angle to the normal to the pitch line equal to the chosen pressure angle of the gear (usually 14½° to 22°). In Fig. 126 is shown an involute pinion and rack, the pressure angle being represented by ψ.

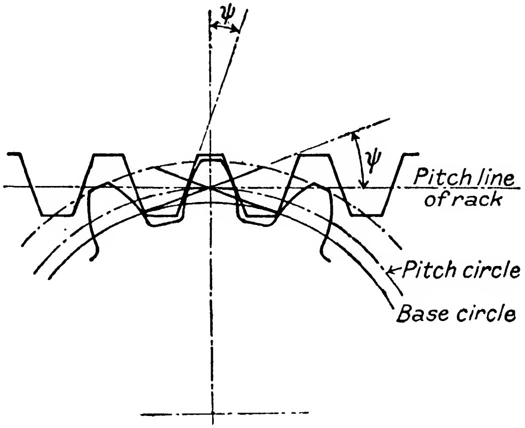


Fig. 126. Rack and Pinion

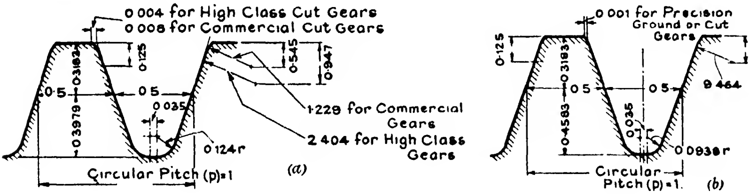

0 004 for High Class Cut Gears
0 008 for Commercial Cut Gears
0·3183
0·125
0·545
0·947
0·5
0 5
0 035
0 3979
0 124r
1·228 for Commercial Gears
2 404 for High Class Gears
Circular Pitch (p)=1
(a)
0 001 for Precision Ground or Cut Gears
0·125
0 3183
3 362
0 5
0 5
9 464
0·4583
0 035
0 7
0 0938r
Circular Pitch (p)=1.
(b)

Fig. 127. B.S.I. Basic Rack Teeth

Fig. 127 (*a*). B.S.I. Basic Rack Tooth. Pressure angle 20°. For high-class or commercial cut gears.

Fig. 127 (*b*). B.S.I. Basic Rack Tooth. Pressure angle 20°. For precision ground or cut gears.

BEVEL GEARING. Bevel gearing is used to connect shafts lying in the same plane whose axes would intersect if produced.

The tooth action is designed to give the same relative motion to the driver and driven shafts as if they were connected by slipless conical friction wheels. The ditch cones must lie symmetrically about their axes and their apices must be coincident.

Fig. 128. Bevel Wheels

B.S.I. Terminology (Fig. 129). **Bevel Wheel and Pinion.**

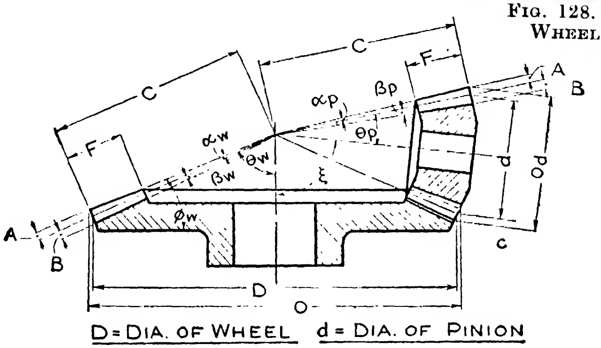


Fig. 129

Name	Symbol
Pitch diameter	D
Cone distance	C
Addendum	A
Dedendum	B
Outside diameter	O
Face width	F
Pitch angle	θ
Addendum angle	α
Dedendum angle	β
Face angle	ϕ
Shaft angle	ζ

Useful Formulae. Bevel Wheels. Shaft Angle 90°.

$$\text{Pitch diameter} = \frac{\text{No. of teeth} \times \text{Circular pitch}}{\pi}$$

$$= \frac{\text{No. of teeth}}{\text{Diametral pitch}}$$

Outside diameter = Pitch diameter + (2 addendum × cosine of pitch angle)

$$\text{Pitch angle (tangent of)} = \frac{\text{No. of teeth in wheel}}{\text{No. of teeth in pinion}}$$

Face angle = Pitch angle + Addendum angle

Cutting angle = Pitch angle − Dedendum angle

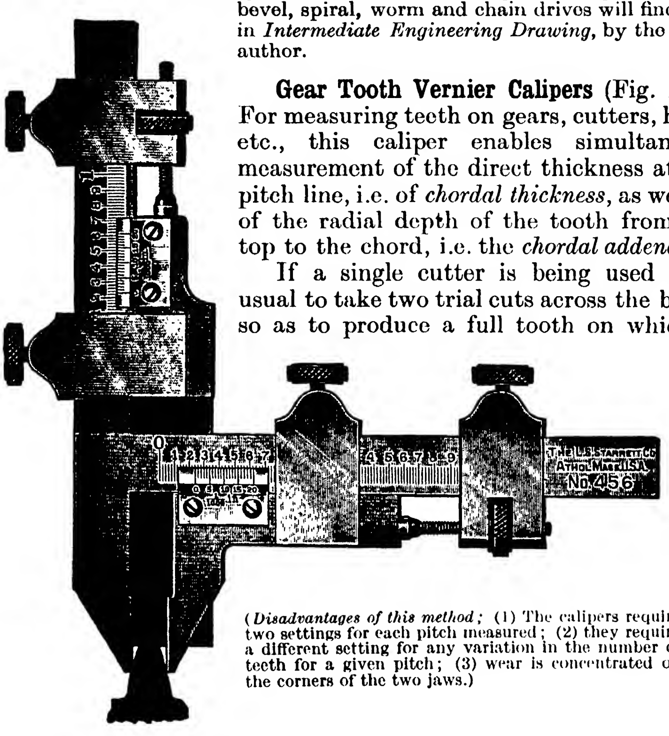
$$\text{Addendum angle (tangent of)} = \frac{2 \text{ sine pitch angle}}{\text{No. of teeth}}$$

$$\text{Dedendum angle (tangent of)} = \frac{2{\cdot}3141 \text{ sine pitch angle}}{\text{No. of teeth}}$$

Other Kinds of Gearing. Space forbids a longer description of toothed gearing in this book. Readers desiring a more extended description of spur, helical, bevel, spiral, worm and chain drives will find this in *Intermediate Engineering Drawing*, by the same author.

Gear Tooth Vernier Calipers (Fig. 130). For measuring teeth on gears, cutters, hobs, etc., this caliper enables simultaneous measurement of the direct thickness at the pitch line, i.e. of *chordal thickness*, as well as of the radial depth of the tooth from the top to the chord, i.e. the *chordal addendum*.

If a single cutter is being used it is usual to take two trial cuts across the blank so as to produce a full tooth on which it may be desired to test the tooth thickness. This is done as follows: the adjustable vertical tongue or scale is set so that when it rests on the top of a tooth the lower ends of the caliper jaws touch the sides of the tooth at the pitch circle. The horizontal scale then shows the *chordal thickness* or *chord length* (dimension *T* in Fig. 131). It must be remembered that the calipers read chordal thickness, but *not* arc length.



(*Disadvantages of this method;* (1) The calipers require two settings for each pitch measured; (2) they require a different setting for any variation in the number of teeth for a given pitch; (3) wear is concentrated on the corners of the two jaws.)

FIG. 130. GEAR TOOTH VERNIER CALIPER GAUGE

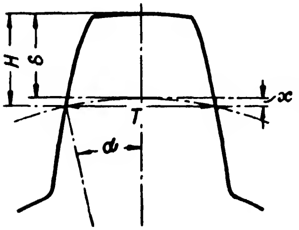


FIG. 131

Useful formulae are as follows—

$$\textit{Arc length} = \frac{1{\cdot}5708}{\text{D.P.}} = \tfrac{1}{2}\ \text{C.P.}$$

The outside diameter of a pinion may be enlarged to avoid undercut, which means that the teeth will be situated on a pitch circle of larger diameter than standard. Therefore the tooth thickness is increased and it will be necessary to use the following rule: Find the difference between standard addendum and the long addendum, and multiply difference by the tangent of the pressure angle; multiply this product by 2 and *add* result to one-half of circular pitch, thus obtaining arc thickness on pitch circle.

This arc thickness cannot be measured by the gear tooth caliper, so that it becomes necessary to obtain the corresponding chord length.

Chord length, or *Chordal Thickness of Tooth*

$$= \text{sin of } \frac{90}{N} \times \text{Pitch diameter}$$

(where N = No. of teeth).

This rule is employed when the outside diameter is standard.

$$\textit{Chordal Addendum} = \text{Pitch rad}\left(1 - \cos\frac{90}{N}\right) + \text{Addendum}$$

Examples

1. A pinion has 15 teeth of 5 D.P. Find the chordal length and the chordal addendum.

$$(a)\ \text{Chordal length} = \sin\frac{90}{15} \times 3$$

$$= 0{\cdot}10453 \times 3 = \underline{\underline{0{\cdot}3136 \text{ in.}}}$$

$$\begin{aligned}(b)\ \text{Chordal addendum} &= 1{\cdot}5(1 - \cos 6^\circ) + \tfrac{1}{5}\\ &= 1{\cdot}5(1 - 0{\cdot}99452) + 0{\cdot}2 = \underline{\underline{0{\cdot}2082 \text{ in.}}}\end{aligned}$$

2. A pinion has 45 teeth of 3 D.P. Find the chordal length and the chordal addendum.

$$\begin{aligned}(a)\ \text{Chordal length} &= \sin 2^\circ \times 15\\ &= 0{\cdot}03490 \times 15 = \underline{\underline{0{\cdot}5235 \text{ in.}}}\end{aligned}$$

$$\begin{aligned}(b)\ \text{Chordal addendum} &= 7{\cdot}5(1 - \cos 2^\circ) + 0{\cdot}3333\\ &= 7{\cdot}5(1 - 0{\cdot}99939) + 0{\cdot}3333\\ &= \underline{\underline{0{\cdot}3379 \text{ in.}}}\end{aligned}$$

3. A pinion has 18 teeth of 1 D.P. Find (*a*) the chordal length, (*b*) the chordal addendum.

$$(a)\ \text{Chordal length} = \sin\frac{90}{N} \times \text{Pitch diameter}$$

$N = 18$; Pitch diameter = 18 in.

$$\therefore \text{Chordal length} = \sin\frac{90}{18} \times 18$$

$$= 0{\cdot}08715 \times 18 = \underline{\underline{1{\cdot}5687 \text{ in.}}}$$

$$(b)\ \text{Chordal addendum} = \text{Pitch rad}\left(1 - \cos\frac{90}{N}\right) + \text{Addendum}$$

$$\text{Addendum of a full depth tooth} = \frac{1}{\text{D.P.}} = 1$$

$$\begin{aligned}\therefore \text{Chordal addendum} &= 9(1 - \cos 5^\circ) + 1\\ &= 9(1 - 0{\cdot}99619) + 1\\ &= \underline{\underline{1{\cdot}0343 \text{ in.}}}\end{aligned}$$

4. A pinion has 30 teeth of 1 D.P. Find the chordal length and chordal addendum.

(*a*) Chordal length $= \sin \frac{90}{30} \times 30$

$= 0{\cdot}05234 \times 30 = \underline{\underline{1{\cdot}5702 \text{ in.}}}$

(*b*) Chordal addendum $= 15(1 - \cos 3°) + 1$

$= 15(1 - 0{\cdot}99863) + 1 = \underline{\underline{1{\cdot}0206 \text{ in.}}}$

THE PIN OR BALL METHOD OF MEASURING SPUR WHEELS. The pin (or ball) method of measuring spur wheels consists of measuring across the outsides of two cylindrical pins (or balls) placed in opposite tooth spaces (of wheels with an even number of teeth) or nearly opposite spaces (of wheels with an odd number of teeth).

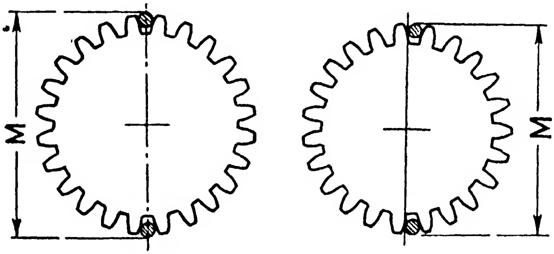


Fig. 132

The pin diameter may be taken as 1·68 ÷ diametral pitch for spur wheels. The following typical pin diameters can readily be checked for practice.

Diametral Pitch . . .	2	4	8	16
Equivalent Circular Pitch .	1·5708	0·7854	0·3927	0·1963
Pin Diameter . . .	0·8400	0·4200	0·2100	0·1050

To find M (see Fig. 132) for external spur wheels use the formula—

$$M \text{ (Even number of teeth)} = D + \frac{Y}{P} + A \quad . \quad . \quad . \quad (1)$$

$$M \text{ (Odd number of teeth)} = \frac{D + \frac{Y}{P}}{F} + A \quad . \quad . \quad . \quad (2)$$

where, M = measurement over pins (or balls).
D = pitch diameter.
P = diametral pitch.
Y = a factor for spur gears.
F = a factor used when number of teeth is odd.
A = diameter of pins (or balls).

These rules apply where there is no allowance for backlash between the teeth. The factors Y and F are given in various engineering handbooks, e.g. *Machinery's* Handbook. Different tables apply to different pressure angles.

Example 1. A spur gear has 43 teeth of 12 D.P., making the pitch diameter 3·583 in. The pressure angle is 20°. Determine measurement *M* for a gear cut without allowance for backlash.

$$M = \frac{D + \frac{Y}{P}}{F} + A$$

$$= \frac{3{\cdot}583 + \frac{0{\cdot}5685}{12}}{1{\cdot}0006} + 0{\cdot}1400$$

$$= \underline{3{\cdot}7683 \text{ in.}}$$

D = Pitch dia. = 3·583
Y = Spur gear factor = 0·5685
P = Diametral pitch = 12
F = Odd tooth no. factor = 1·0006
A = Dia. of pin = 0·1400

Example 2. A spur wheel has 50 teeth of 10 D.P., making the pitch diameter 5 in. The pressure angle is 14½°. Determine the measurement *M* for the gear, which is cut without allowance for backlash.

$$M = D + \frac{Y}{P} + A$$

$$= 5 + \frac{{\cdot}58800}{10} + 0{\cdot}1680$$

$$= \underline{5{\cdot}2268 \text{ in.}}$$

$D = 5$
$A = 0{\cdot}1680$
$P = 10$
$Y = 0{\cdot}5880$

Gear Tolerances. These are usually placed on the gear centres, tooth thickness, blank (outside) diameter, root diameter, and on precision work a grinding allowance is given on the thickness of tooth.

Inspection of Gear Wheels Supplied as Spare Parts for Aero Engines. (See Inspection Leaflet No. 120.) These are usually tested on special rolling jigs on which the clearance between teeth is checked at several positions, and should be "run in" against master gears. Engine reduction gears, and similar large units, must be mounted, together with their pinions, on a suitable rig and run in, to secure satisfactory bedding of the teeth. After check testing, each pair should be regarded as a single integral unit and should be "permanently paired" by similar markings and by wiring them together.

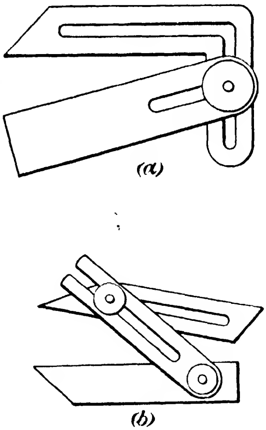


FIG. 133. SIMPLE BEVEL GAUGES

MEASURING ANGLES. The common bevel gauge is set by means of a plain protractor which is divided in degrees. It may also be set to a sine bar. Its more general use is to transfer angles from one job to another. At (*a*) in Fig. 133 is shown a useful bevel consisting of a blade and stock adjustable by means of a screw with knurled nut. At (*b*) is shown a combination bevel. A stud is riveted in the stock and on this hinges the split blade. The slotted auxiliary blade may be slipped on to the split blade and adjusted at any angle. The stock and the auxiliary blade will lie flat on the surface of a job.

In the precision measurement of angles there are two methods in common use: one is the vernier protractor which can be set to the desired angle within 5 minutes of a degree, the other is that known as the sine bar, so called because the sine of the angle, and not the angle itself, is measured.

Bevel Protractors. A typical bevel protractor is shown in Fig. 134. The blade can be slid along its entire length and clamped. It can be set to any angle relative to its base and clamped with the central stud. The dial is graduated in degrees round the entire circle, the lines being sunk slightly below the surface. A vernier is fitted which reads to 5 min. or $\frac{1}{12}^\circ$.

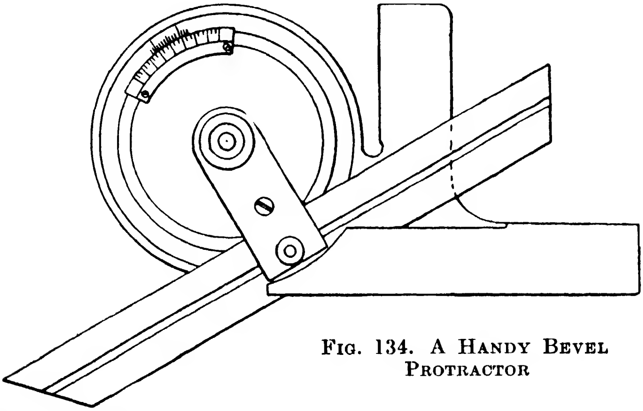


Fig. 134. A Handy Bevel Protractor

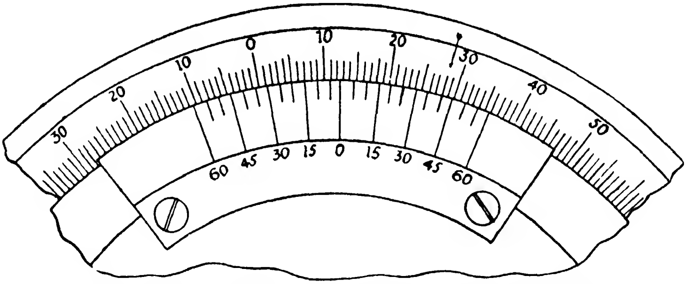


Fig. 135. An Enlarged View of the Vernier
Reading: 12° 40′

The method of reading is shown in the enlarged diagram, Fig. 135. Each space on the vernier is 5 min. shorter than two spaces on the main scale. When the 0 line on the vernier coincides with the 0 line on the main scale, the edges of the base and blade are parallel. When the swivel head is moved so that the line on the vernier next to 0 coincides with the line next but one to 0 on the main scale, the angle between the base and the blade is 5 min. or $\frac{1}{12}^\circ$. Hence the rule reads off directly from the main scale the number of whole degrees between the 0 on the main scale and 0 on the vernier. It is then necessary to count in the same direction the number of spaces from the 0 of the vernier scale to a line that coincides with a division on the main scale. If this number is multiplied by 5, the product will be the number of minutes to be added to the whole number of degrees. In Fig. 135 the 0 line on the vernier has moved 12 whole degrees from the 0 line on the main scale, and the eighth line on the vernier coincides with a line upon the main scale, as indicated by the arrow. Multiplying 8 by 5, the product, 40, is the number of minutes to be added to the degrees. The reading is thus 12° 40 min.

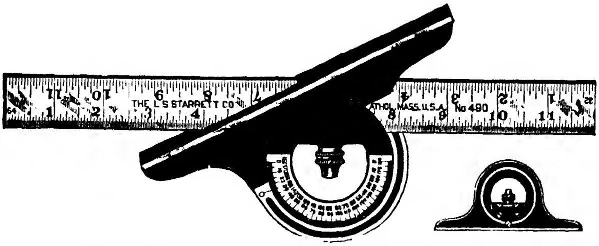


FIG. 136. A USEFUL STARRETT PROTRACTOR

Fig. 136 shows another popular protractor often sold in combination with a *centre-square*. As the head extends on both sides of the blade, angles can be transferred from either side without resetting.

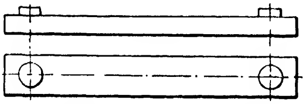


FIG. 137. A SIMPLE SINE BAR

The Sine Bar. This is very simple in design consisting of a bar carefully machined and ground and having two cylindrical studs or plugs (hardened steel) as shown in Fig. 137. The centres of these plugs are in the exact centre of the bar, their centre distances being some even size, generally 5 in. or 10 in. The bar usually has a slot or slots to enable it to be clamped against an angle plate or a slotted object.

The Sine of an Angle. In Fig. 138 we show the right-angled triangle ABC. It is conventional to letter sides a, b, c opposite respectively to the angles A, B, C. To find the sine of angle A it is necessary to divide the length of side a (the "opposite side") by the length of side c (the "hypotenuse").

Thus $\text{Sine } A = \frac{a}{c}$

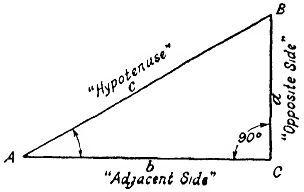


FIG. 138

Suppose $a = 2$ in., $c = 3$ in., then the sine of $A = \frac{2}{3} = 0{\cdot}6667$. Having got the sine we wish to find the angle. This is done by referring to a *table of sines*. In the case dealt with we find that the angle is 41° 49′ (41 degrees, 49 minutes).

When we use the sine bar, as we show subsequently, the stud centre-distance can be taken as the hypotenuse of a right-angled triangle.

A Simple Sine Bar (Fig. 139). The angle plate A is perfectly square. Clamped to it is the parallel strip B, to which are attached the cylindrical plugs C. The component is laid on a surface plate, on which the angle plate A is resting, and is measured by placing it against the parallel strip B. The latter is called the sine bar. The centre distances of the plugs B being known, and the difference of their distances from the surface plate, the sine of the angle can be worked out. On reference to a "trig" table the angle can then be obtained.

Modern sine bar testing blocks and angle measuring fixtures are made by the Pitter Gauge and Precision Tool Co. Ltd., Woolwich, S.E. These are used in conjunction with precision measuring blocks and slip gauges, working from a flat lapped surface such as a toolmakers' flat, which thus forms a bottom datum face.

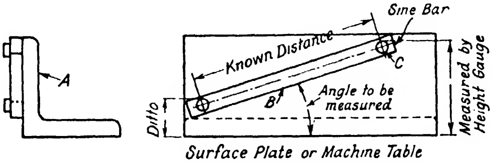


FIG. 139. A SINE BAR MOUNTED ON AN ANGLE PLATE

Calculation for Setting of Sine Bar. Fig. 139B (*a*) shows a sine bar of common form. Its ends are stepped and a roller is gripped tightly into each step by means of a screw. In all sine bars it is essential that the rollers or plugs be of the same diameter, be absolutely parallel, and have their centres at an exact distance (for ease of calculation 10 in. is convenient). Then, too, the centre line of the plug centres (CL in Fig. (*a*)) *must* be parallel to the *measuring face* of the bar, so that it is best to have *both* upper and lower faces of the bar truly parallel.

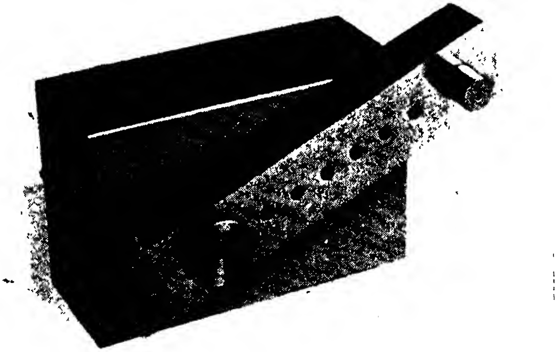


FIG. 139A. P.V.E. ANGLE-MEASURING FIXTURE ON SINE-BAR PRINCIPLE

Consider the bar set as in Fig. (*b*), its rollers D and F resting on piles of slip blocks.

$$\frac{FE}{FD} = \frac{h}{C} = \sin \alpha. \text{ Then } h = C \sin \alpha.$$

Example 1. Work out the setting of a 10-in. sine bar to measure an angle of 39° 36′.

$$\text{From tables, } \sin 39^\circ\ 36' = 0{\cdot}6374$$

$$h = 10 \times 0{\cdot}6374 = 6{\cdot}374''.$$

Thus one plug must be set 6·374 in. above the other.

Example 2. It is required to arrange the setting of a 5-in. sine bar to check the angle of a taper; the total taper of which is $\frac{5}{8}$ in. per foot and length 12 in. See Fig. (*c*).

See the triangle ABC. $CB = 12$ in., $AB = \frac{5}{16}$ in., Angle $ACB = \frac{\beta}{2}$

$$\tan \frac{\beta}{2} = \frac{\frac{5}{16}}{12} = \frac{5}{192} = 0{\cdot}02604$$

From tables, Angle $\frac{\beta}{2} = 1^\circ\ 29{\cdot}5'$,

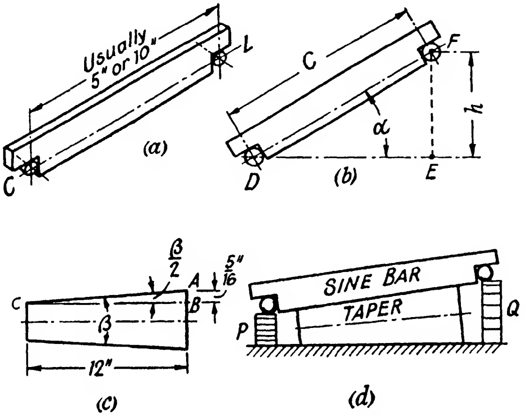
and $\beta = 2^\circ\ 59'$

Now $\sin \beta = \sin 2^\circ\ 59' = 0{\cdot}0520$.

Since the setting is for a 5-in. sine bar,

$$h = 5 \times 0{\cdot}0520$$
$$= 0{\cdot}260 \text{ in.}$$

The sine bar provides a reliable method of measuring angles up to, say, 45°. For angles above this, to 90°, it is less accurate. Useful tables of "Setting Constants for 5-in. Sine-Bars" are obtainable from "Speeditype," "Dorack," Kemishford, Mayford, near Woking, Surrey, price 1s. 7½d.



(c) (d)

Fig. 139B

Angle Block Gauges. The N.P.L. has done much to develop angle block gauges, which make it possible to set a face within two seconds of any required angle to the surface on which a number of these blocks are placed. Thus in Fig. 139C the four angle blocks are arranged so that the angle between surfaces *AB* and *CD* equals the *sum* of angles 1, 2 and 4, *minus* the angle 3. The blocks have truly plane and parallel end faces which can be wrung together in the same way as parallel slips and blocks.

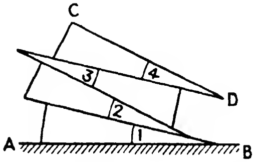


Fig. 139C

Optical Protractors. These are modern appliances for measuring angles on high precision work quickly, easily, and accurately to very close limits.

The Bausch & Lomb Optical Protractor is well known and can therefore be described as a further typical example of the application of optical principles to practical production and inspection.

It is used for measuring and checking the exact angular relation between surfaces, edges, and holes. It does the same work as the sine bar, with the advantage over it that direct reading replaces much trigonometrical calculation and reference to tables in handbooks. Thus opportunities for error are minimized and no mathematical facility is required on the part of the operator. Then, too, it avoids the use of accessory equipment required when the sine bar method is used. The Optical Protractor can be used for setting up and inspection work on jigs, boring, milling, drilling machines, etc., and for measuring angles on tapers, dovetails, grooves, etc.

It is built on an adjustable vee-slotted base of hardened and ground steel and the ring centre of the instrument revolves carrying with it a "spirit level" vial and a vernier protractor scale which is viewed through an eyepiece.

In use, after truing the base, the centre ring is merely revolved by hand or by the micrometer screw which acts as a fine adjustment until the required angle appears on the scale. The protractor is next placed on the work, which is then turned until the level bubble becomes central. Illustrated particulars obtainable from Bausch & Lomb Optical Co. Ltd., Africa House, Kingsway, London, W.C.2.

Measurement of Angular Movement. Angular movement of a work-piece about an axis can accurately be measured by applying the sine bar principle in conjunction with a surface plate and block gauges.

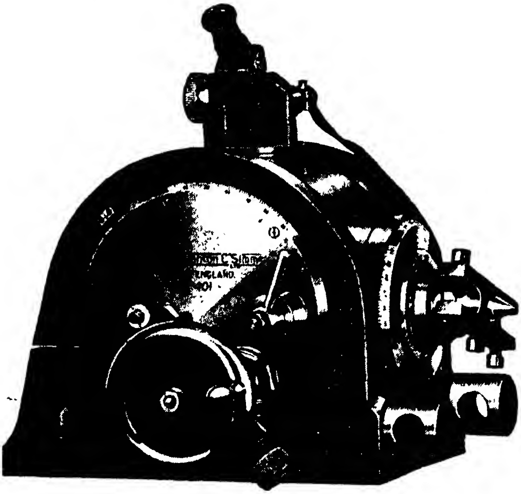


FIG. 139D. COOKE OPTICAL DIVIDING HEAD

This, however, when measuring the angular spacing of teeth in serrated jobs such as gear wheels, is slow inasmuch as it involves reference to trig. tables. Thus for many such jobs the "divided circle" method is found most suitable. The Zeiss Angular Division Tester is typical of a range of instruments designed for this work.

The Cooke Optical Dividing Head (Fig. 139D). This dividing head, marketed by Cooke, Troughton & Simms, of York, is designed and built to provide a standard of angular measurement to satisfy the most exacting requirements in engineering.

The usual "mechanical" form of dividing head often causes errors due to irregular spacing of the holes in the notch plate or to inaccuracy of the worm and worm-wheel. In the optical dividing head the worm gear has no function of measurement and is used solely for rotating the spindle. Mounted co-axially with the main spindle is a *graduated circle*, the movement of which is observed with a micrometer microscope. The graduations are marked on a glass annulus mounted on the spindle. Great care is taken in centring the circle, that is to say in seeing that the point from which the circle graduations radiate lies on the mechanical axis about which the spindle rotates. The inherent accuracy of this remarkable instrument is in the order of 10 seconds of arc, i.e. when it is used for *measuring* and is unaffected by exterior conditions. When used for machining purposes, however, degree of accuracy necessarily depends on the manner in which the machine is used. Fully illustrated particulars are available from the makers.

The Clinometer. This is essentially an instrument for measuring angles relative to the horizontal plane, but by addition and subtraction it is possible to check the angles between two parts of a job even if separated by considerable distances or on different levels. Whilst there are various makes and types of clinometers they are designed on one of two basic principles. One involves the use of a spirit level and checking from the horizontal, the other makes use of the plumb-bob principle and works from the vertical.

The Cooke Optical Clinometer (Fig. 139E). This forms a useful accessory to the dividing head previously explained, and is designed for general use by toolmakers and inspectors. Here, too, the accuracy depends upon the graduation of a circle, and there are no screws, worms or racks concerned with the function of measurement.

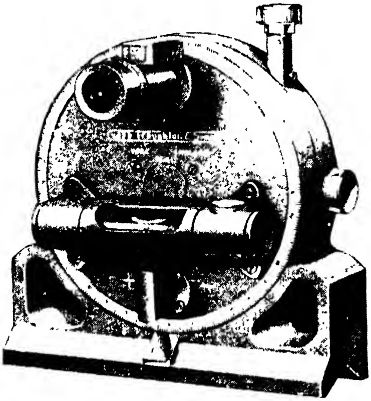


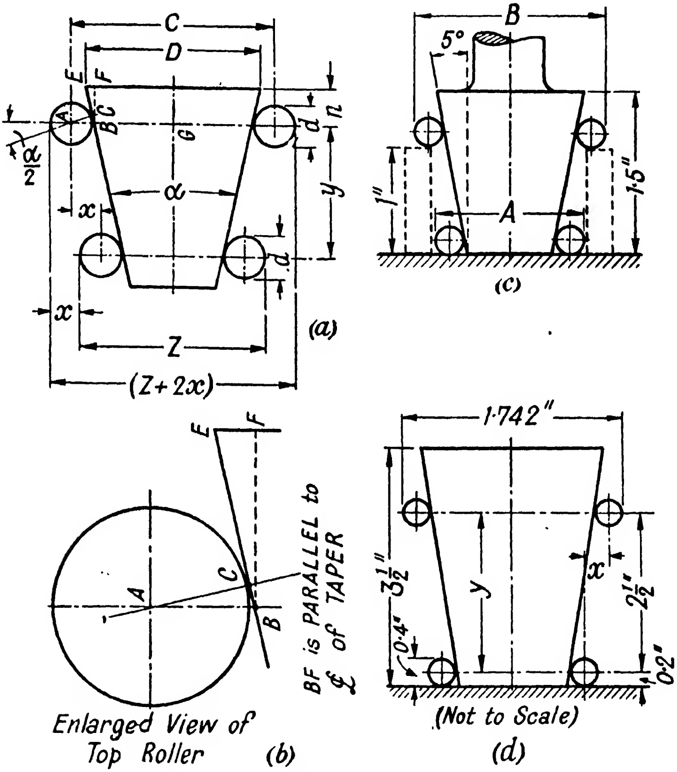
FIG. 139E. COOKE OPTICAL CLINOMETER

The graduation, which is to degrees, is imprinted on a glass annulus and is observed by a high-power microscope. For sub-division a reticule of 60 divisions, corresponding to one degree on the circle, is placed in the focal plane of the objective, thus 1 division = 1 division of arc. Light from an external source passes through the annulus and microscope to the eye, and is impeded by the graduations, which in consequence appear to be jet black against a field as bright as the user cares to make it. The clinometer consists of two main components revolving one about the other upon a finely ground bearing. The base, which carries the circle, is of cast iron, and on the underside is of vee and plane form. The upper element, on which is mounted the microscope containing the subdivision reticule and the spirit level, is of gunmetal. The light for illuminating the reading system is admitted through an aperture on the top of the element carrying the spirit level and in consequence always remains in that position whatever the angle under observation. The level is designed to register a movement of 30 seconds per 2 mm. run. Illustrated particulars are obtainable from Messrs. Cooke, Troughton & Simms, Ltd., Kingsway North, York.

Measuring a Taper Plug by Means of Rollers. Fig. 139F (*a*). Suppose two pairs of equal cylinders are placed on opposite sides of the tapering piece.

$$x = y \tan \frac{\alpha}{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

If dia. over outsides of lower rollers $= Z$, then dia. over outsides of upper rollers $= Z + 2x$.



Enlarged View of Top Roller (*b*)

(Not to Scale) (*d*)

FIG. 139F

If the dia., *D*, at the top of the taper is to be calculated we may proceed thus—

Let n = distance of top of taper from centre of top rollers. Consider triangle *ABC*.

$$\frac{AC}{AB} = \cos \frac{\alpha}{2} \quad \left(\text{Note that } AC = \frac{d}{2}\right)$$

$$\frac{d}{2\,AB} = \cos \frac{\alpha}{2}, \text{ whence } AB = \frac{d}{2 \cos \frac{\alpha}{2}}$$

$$BG = \frac{D}{2} - EF = \frac{D}{2} - BF \tan \frac{\alpha}{2}$$

$$= \frac{D}{2} - n \tan \frac{\alpha}{2}$$

$$C = \text{roller centres} = 2\,(AB + BG)$$

$$= 2\left(\frac{d}{2\cos\frac{\alpha}{2}} + \frac{D}{2} - n\tan\frac{\alpha}{2}\right) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

If C, d, n are known, we can find D by transposition, thus—

$$\frac{D}{2} = \frac{C}{2} + n\tan\frac{\alpha}{2} - \frac{d}{2\cos\frac{\alpha}{2}}$$

whence, $D = C + 2n\tan\frac{\alpha}{2} - \dfrac{d}{\cos\frac{\alpha}{2}}$ . . . . (3)

Generally, as mentioned in Chapter IX, the governing points when measuring non-standard tapers of round section are the diameter of the large end and the amount of taper.

Fig. 139F (*c*). Suppose we wish *to check the taper* and are given (1) included angle of taper 10°, (2) total length of taper 1·5 in., (3) cylinders of 0·2 in. dia.

Measurement is made of the over-cylinder diameters A and B, the cylinders being one-inch apart as shown. The difference between these diameters should be $B - A = 2\tan 5° = 0{\cdot}1750$ (in.).

Fig. 139F (*d*). A taper of 1 in 8 on the dia. is 3½ in. long. It is to be checked by means of rollers 0·4 in. dia. with their centres 2½ in. apart as shown. The dia. over the top rollers is 1·742 in. What is the reading over the bottom rollers?

Centre distance over top rollers = 1·742 − 0·4 = 1·342 in.

$\frac{x}{y} = \frac{1}{16}$. Whence $x = \frac{y}{16} = \frac{2\frac{1}{2}}{16} = 0{\cdot}15625$ in.

Micrometer reading over bottom rollers

$$= 1{\cdot}342 - 2\,(0{\cdot}15625) + 0{\cdot}4 = 1{\cdot}4295 \text{ in.}$$

Checking Hole Taper by Means of Balls. Fig. 139G. Two balls have been selected so that they lie touching the tapering surface of the hole. Balls should be selected which will give some clearance between them, thus yielding a centre-distance C which can be measured without trouble. Thus in the arrangement shown the dimension E can be measured with a depth gauge. Dimension J can be measured by a height gauge, after which it is possible to calculate dimension C by simple arithmetic.

It can then be shown that,

$$\sin\frac{\alpha}{2} = \frac{R - r}{C}$$

a simple formula which enables us to calculate the included angle α.

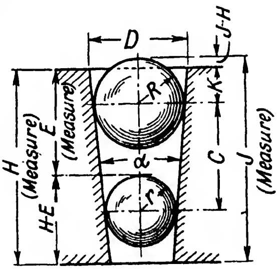


FIG. 139G

If it is desired to calculate the dia. D at the top of the hole, the following formula can be used—

$$D = 2\left(R\sec\frac{\alpha}{2} + K\tan\frac{\alpha}{2}\right)$$

Caution. Measurements made by means of balls and rollers are based on very small contact surfaces. It is thus essential that contact pressures be maintained constant.

CHAPTER XII

METAL JOINING BY SOLDERING, BRAZING, WELDING, AND RIVETING

In aero inspection a certain amount of hard and soft soldering work is encountered, e.g. on steel tubing, radiator casings, tanks, etc., so that a few hints will be useful to many, whether interested in aero or general inspection.

Solders. Soft solders consist chiefly of lead and tin in varying proportions, although other metals are occasionally added to lower the melting-point. Many solders have been standardized. See B.S.S. No. 219 (*A* to *K*; grade *A* being for sweating and *B* for general tinsmiths' and coppersmiths' work). See also D.T.D. Spec. No. 81 and No. 221.

The hardest alloy contains 66 per cent tin and 34 per cent lead, with a Brinell hardness number of 16·7 and a melting-point of about 356° F., or 180° C. Lead-tin alloys are *eutectic alloys*, i.e. they are examples of the combination of two metals melting at a temperature lower than either of them would if melted separately. The commonest and cheapest solders have the most lead and the highest melting temperatures.

Fluxes. Parts to be soldered and tools employed must be perfectly clean and oxidization of the surfaces must be prevented or the solder will not "flow" or "run." Oxidization is prevented by using a coating of some substance that melts at the fusing temperature of the solder and thus excludes the air. It must have a solvent action on the oxide. In general engineering work the fluxes used for soft soldering include (1) *zinc chloride* ("killed spirit") for tinned plate (iron or steel), brass, gun-metal, copper; (2) *hydrochloric acid* for zinc and galvanized steel; (3) *stearin* for aluminium.

The surfaces of articles to be soldered are first thoroughly smoothed, cleaned, and tinned. (The parts are sometimes pickled in a dilute acid bath, after which thorough washing in boiling water is necessary. One effect of this washing is to prevent "hydrogen embrittlement." After boiling, the parts should be heated to 150° C.) The flux is then added and the solder melted by means of a soft non-luminous gas flame or soldering iron applied to the work in order to raise it to such a temperature as to make interpenetration complete. The chief thing in soldering is to use the right flux in conjunction with a suitable-sized "iron"—well tinned and hot.

The inspection of the flux used is necessary to see that it is free from mineral acid. It should be issued fresh daily. Without these and other precautions there is danger of subsequent corrosion at the joint. After diluting the flux by adding an equal quantity of water it is tested by dipping into it a methyl orange paper. The presence of mineral acid is indicated if the paper turns pink. Fluxes in solid form should be lab-tested from time to time and care taken to use them in strict accordance with approved directions.

Readers interested in solders and anti-friction metals should apply to The Hoyt Metal Co. Ltd., Putney, S.W.15, for the *Hoyt Bulletin* and other useful publicity matter.

Soldering Copper Strip. When soldering copper strip a hard tin-copper compound is formed on the copper surface, where cracks are liable to initiate and propagate. To overcome this difficulty lead containing a little silver is used as the solder.

Silver Soldering. Silver solder contains silver as well as copper and zinc. See B.S.S. No. 206. Borax is used as a flux. A red heat is necessary and the methods employed are similar to those used in brazing.

Brazing. This is really a high-temperature soldering operation giving a very strong joint, using borax as a *flux*, and one or other of the copper-zinc (i.e. brass) alloys as the *spelter.* This may be in the form of filings, a thin stick, or wire.

As the proportion of zinc increases so the melting point of the spelter is lowered, thus a spelter should be chosen having a melting point as close as possible to that of the articles being brazed so as to secure a tenacious joint.

In **dip brazing** the parts to be brazed are immersed in a bath containing the molten spelter until the parts are heated sufficiently to be united. The temperature of the bath should not exceed 900° C. Largely used for many years past in the cycle industry this method is now extensively used on airframe work. On such work the jobs are usually normalized after brazing so as to prevent subsequent cracking and fracture. See B.S.S. No. 263—1926.

When using a brazing bath the spelter should contain 55 per cent copper and 45 per cent zinc. Some of the zinc will be lost by volatilization and must be made good periodically to maintain the composition and prevent undue rise in temperature. So as to keep the zinc losses as low as possible, the surface of the molten metal should be covered with a layer of borax and powdered charcoal.

Soft Soldering of Stainless Steel. Detailed instructions on the process inspection of this will be found in Inspection Leaflet No. 405 in the *Airworthiness Handbook.*

Inspection of Soldering and Brazing. For inspection hints regarding **aero work,** see Inspection Leaflet No. 405 (A.P. 1208). The quality and soundness of soldering or brazed work cannot generally be properly ascertained by testing or examining the finished article. Inspection of this, as of certain other jobs, depends largely for its efficiency on *process inspection,* i.e. supervision of the details of the processes involved. Inspectors interested in this work are referred to the official leaflet mentioned above.

Stelliting. Stellite is composed principally of cobalt, chromium, and tungsten, the amounts of these respective constituents varying with the degree of hardness required. Its main advantage lies in the great resistance it offers to wear and oxidization, especially at high temperatures. It is therefore **used in aero work** for facing valves, valve seats, and rockers.

The Process. It is not a welding process inasmuch as it is undesirable that fusion should occur with the material under treatment. It may, however, be compared with brazing. In essence the process consists of applying a layer of stellite to the surface of the material by means of an oxy-acetylene torch. Parts which have been stellited may be given heat treatment to remove any stresses set up by the stelliting process.

Inspection. Fully detailed in Inspection Leaflet No. 400.

WELDING

Forge Welding. In forge, or blacksmiths', welding of wrought iron or low-carbon steel the parts are raised to a plastic condition at white heat in a clean fire and hammered together. The slag in wrought iron acts as a flux, but for steels sand is used. The range of applications of forge welding is becoming narrower.

Autogenous Welding usually consists of uniting two pieces of metal, without compression or hammering, by means of a third metal of approximately the same analysis which is fused between the parts. By some methods, however, the weld is made without a flux and without introducing new material to form the joint. The following notes indicate briefly the main characteristics of various welding methods.

Oxy-acetylene Welding. See B.S.S. No. 693—1936. The oxy-acetylene blow-pipe flame is obtained by igniting a mixture of two gases, viz. oxygen and acetylene, in correct proportion and at proper pressures. It is said to give temperatures up to 6 000°–7 000° F. which will melt all ordinary metals.

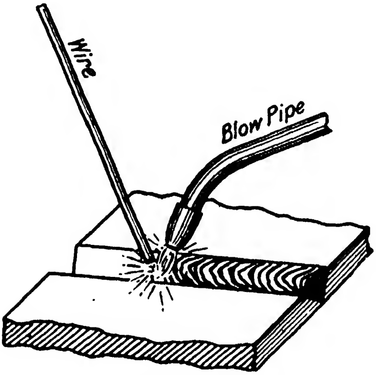


FIG. 140. WELDING A BUTT JOINT

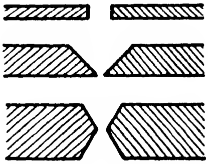


FIG. 141. PREPARATION OF PLATES FOR BUTT JOINTS

For a large range of British and American welding definitions and illustrations see "Blueprint Reading Simplified" by the same author.

If the blow-pipe flame is formed by the correct mixture of gases it yields products of combustion which tend to protect the metal from oxides and also from surface scale when the metal is in a molten state. It will neither oxidize nor carbonize the metal. A good welder, on the thinnest plates to heavy metal, can produce welds up to 95 per cent the strength of the solid plate, but this in general is a high figure.

In brief the procedure is as follows. The metal pieces to be welded are preheated at the line of contact by the torch flame. When the *base metal* is at molten temperature the *weld metal* is added by using the torch flame to melt a *filler rod.* The molten metal forming the weld is in a small pool over which the flame is continually played. To run a weld along a joint this pool is caused to move, melting metal ahead of it as it goes and letting the metal cool behind it.

The feeding wire should be of a quality suited to the grade of work. For welding mild steel the welding rod should be low in carbon. Welding rods for cast iron should be of fine grade cast iron. Cast aluminium welding rods should be used for aluminium castings, but drawn rods are used for aluminium sheet (see Fig. 140), where is shown the wire and blow-pipe applied to a butt joint. Bevelling the edges of the abutting plates is recommended for plates over ⅛ in. thick, the filling metal being added to the vee-shaped channel. Thick plates are bevelled and welded on both sides. Fig. 141 shows the preparation of plates of graded thickness for butt joints.

Metal Cutting. A special form of blow-pipe called a "cutting torch," is used for cutting metal. It is so arranged that a central stream of oxygen can be brought into the flame which rapidly cuts the metal away by oxidization. It is useful for "flame cutting" unusual metal shapes before assembling parts together by welding.

Fig. 142 shows a typical aero welding job, viz. welding the engine mounting of an Armstrong Whitworth Whitley bomber with *British Oxygen Company's* equipment.

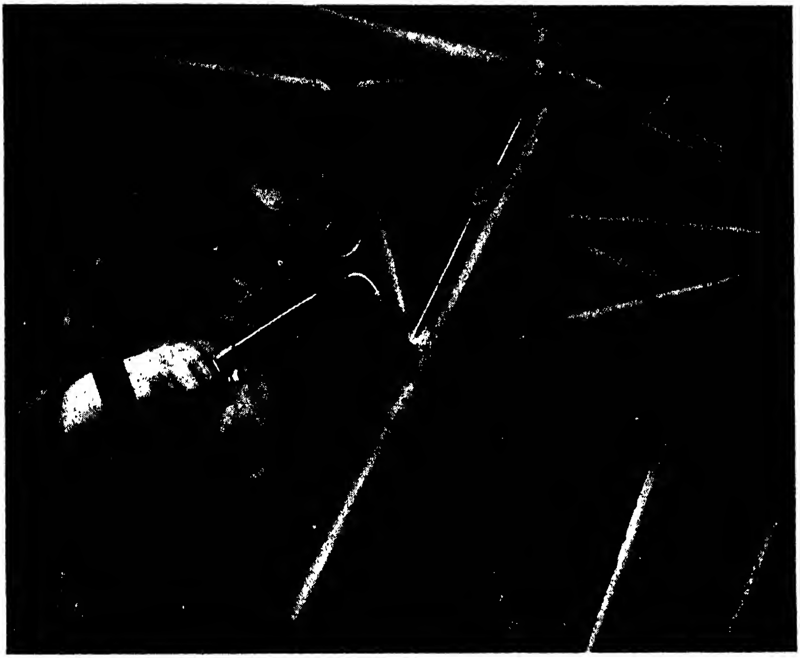


FIG. 142. WELDING THE ENGINE MOUNTING OF A BOMBER

Electric Welding. Two main methods of heating metals up to welding temperature by means of an electric current will be mentioned, viz. (1) resistance welding and (2) arc welding.

1. **Resistance Welding.** This has been described as a "heat and squeeze process" in which a heavy electrical current, at low voltage, is passed through the contacting surfaces of the metals to be welded so as to raise them to the temperature of fusion. The electrical resistance of the metals at the contacting surfaces is so high that they become heated immediately to a welding temperature. Pressure is then applied mechanically to complete the weld. The electric current is used simply as a source of heat.

This general process of resistance welding is divided, according to the way in which the parts are welded together, into several processes or methods, e.g. butt welding, spot welding, flash welding, seam welding, etc.

Butt Welding. Pieces, e.g. bars, tubes, rods, wires, having the same (or nearly the same) cross-section are laid end to end, securely clamped by suitable electrodes. The current passes from one piece to the other until the metal at the ends is fused. The pieces are then squeezed together by mechanical means and welded.

Spot Welding. This is for light sheet work, etc., the pieces being overlapped and fused at different points. Pressure is applied and the welds made in spots. This method has displaced a good deal of light riveting.

Flash Welding. This is a special application of butt welding.

Seam Welding. The pieces to be joined are overlapped and squeezed together while hot, leaving the welded joint practically the same thickness as the stock material, and producing the effect of a continuous seam.

The resistance welding method is best suited for the mass production of identical pieces because special equipment and set-up is needed for many jobs.

2. **Arc Welding.** In this process one wire of an electric circuit is joined to the part to be welded and the other is connected to an electrode which is held in a suitable holder. The arc is formed across the short air-gap between the work to be welded (positive terminal) and the electrode (negative terminal). The instant the arc is formed, the temperature of the work at the point of welding and the welding electrode jumps to about 6 500° F. This is an exceedingly high temperature and is concentrated at the point of welding and the end of the electrode, its effect being to melt a small pool of metal in the work and to heat the end of the electrode. Further metal required is obtained from the electrode, if a metallic electrode is used, or from a filler rod (which is fed into the arc, melted and deposited). The use of filler rods is possible with either carbon or metal electrodes.

Metallic Arc Welding. The arc is formed between the work and a metal wire of the same or very similar material. Due to the intense heat of the arc a small part of the work is brought to melting-point. The tip of the metal wire, which comprises the other end of the arc, is also melted—so that small globules of metal are formed. These are forced *across the arc* and so deposited in the molten part of the work.

Carbon Arc Welding. In this process the arc is drawn between the work (which forms one electrode for the circuit) and a carbon rod (the other electrode) which is secured in a holder and manipulated by the operator. The great heat causes the melting of a small part of the surface of the work. This is kept molten by playing the arc across it, additional metal for forming the weld being added by a filler rod. This method, unlike metallic arc welding, is unsuitable for vertical or overhead welding.

Thermit Welding. In essence this is a casting process for joining iron and steel, employing a chemical reaction obtained by igniting a mixture of finely divided aluminium and iron oxide.

Aluminium has a great affinity for oxygen when a high temperature is applied locally. Consequently during the reaction the oxygen leaves the iron oxide to combine with the aluminium. So fierce a chemical action is set up that within a few seconds a quantity of boiling thermit steel, at about 5 400° F. can be prepared in a crucible ready for the purpose. It can be drawn off into a mould specially prepared around the parts to be welded. The latter are cleaned and then brought to a red heat before the molten metal is poured into the mould, where it fuses and amalgamates with the broken sections, thus forming a homogeneous weld. This process requires a range of accessories and equipment and is best suited for the repair of heavy iron and steel parts, tramway lines, etc.

Welding Replaces Casting. Autogenous welding has enabled economic re-design of many engineering parts previously cast in sand moulds. Steel is much stronger, stiffer, and more reliable than cast iron.

For economy standard steel sections are used where possible, and the "fabricated" (or welded) substitutes for the rounded and tapering heavier castings often have a jarring appearance at first. However, the eye soon accustoms itself to the changed appearance, especially in view of the extensive economies which can be effected, e.g. (1) *no patterns required* (this saves the cost of pattern drawings, pattern storage, and repairs), (2) *material costs are lower.* Steel is stronger, stiffer, and more ductile. It offers higher resistance to fatigue, is generally more uniform and dependable, and yet is less expensive than cast iron.

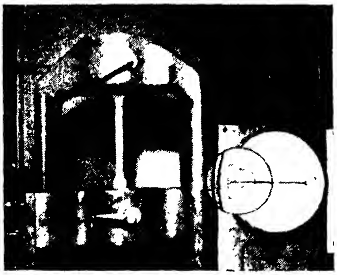


Fig. 143

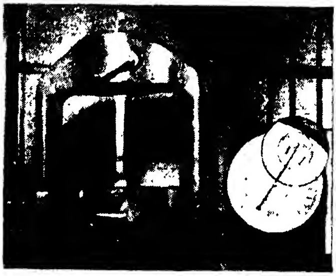


Fig. 144

This is illustrated in Figs. 143 and 144. Two equal-sized bars were pulled to failure. The cast iron bar in Fig. 143 broke at 16 420 lb. per sq. in., whereas the mild rolled steel bar in Fig. 144 withstood a loading up to 61 800 lb. per sq. in., the tests being performed by the Lincoln Electric Co., Ltd. In Fig. 145 two bars of equal size are shown, one being mild steel and the other cast iron, each being fixed at one end. Equal weights were then placed on each bar at the unsupported ends. The cast-iron bar deflected twice as much as the steel bar.

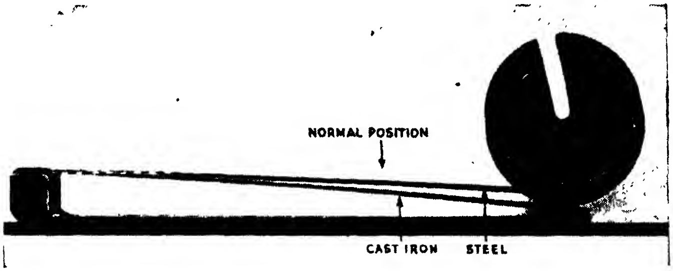


Fig. 145

Inspection of Welds. Visual inspection is the most usual and it presupposes on the part of the inspector a knowledge of the correct procedure in making welds. Visual inspection may be made during or after welding. During actual welding it is possible to see the *inside* of the joint. Naturally it is impossible for an inspector to watch every weld and therefore it is usual to arrange for observation of a percentage number done by every operator. When examining joints *after welding* an experienced inspector will recognize certain unmistakable signs of efficient or inefficient workmanship, e.g. size and shape of bead, undercut, overlap, location of craters (indicating where the operator started and finished welding). For inspection all welds should be left in the "as welded" state, i.e. no "cleaning," e.g. filing, grinding or machining being allowed. *During welding* there are four main items to watch, viz. (1) the burn-off of the electrode, (2) the fusion, penetration, and crater, (3) the formation of the bead, (4) the sound of the arc. These four tell-tale signs indicate to the welder or observer that proper procedure is being followed.

FIG. 146. RADIOGRAPH OF MILD STEEL BUTT WELD

As the usual inspection of a finished weld is confined to visual examination the inspector is compelled to rely on (1) the use of approved materials, (2) the approval and maintenance of the standard of efficiency of the welders, (3) the use of approved methods. Details of the **Air Ministry** requirements as to *materials* will be found in Inspection Leaflets Nos. 39 and 145. In regard to *qualifications of welding operators* it can be said that various sets of tests have been devised in this and other countries in relationship to the type of work normally handled by the particular operators. For ordinary commercial welding it may suffice to set as test pieces lap, butt, or right-angled "fillet" joints made horizontally on the size of plate usually handled. If the welder cannot satisfactorily weld a lap joint with good penetration to the root of the weld, and good fusion at both sides of it, he should be disqualified. If he is liable to be called upon to do vertical welding the tests previously mentioned should be made on joints in vertical positions. A vertical lap joint is quite a difficult test.

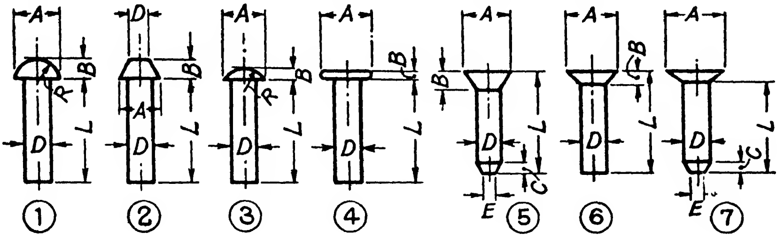
To meet **A.I.D.** requirements the inspector must *verify that welders have been proved competent*; the proof taking the form of a satisfactory report by the A.I.D. Test House No. 2, Cardington, upon standard test specimens prepared by each welder. Full details of these tests on plates and tubes are given in Inspection Leaflet No. 39.

Inspection by X-ray has been used for some time past to check that continuous fusion has taken place all along a seam. Fig. 146 shows an X-ray "radiograph" of a mild steel butt weld. An experienced operator will at once detect lack of fusion at the vee-faces and also between runs. B.S.I. tests for oxy-acetylene welds are given in B.S.S. No. 693—1936.

RIVETS AND RIVETING. Riveting is the simplest method of joining materials together to give a permanent fastening. In Fig. 147

are shown the various types of rivets *up to ½ in. diameter* as detailed in B.S.S. No. 641—1935. The table gives the sizes of *A*, *B*, etc., in terms of *D* (diameter). In addition to the types shown manufacturers have recently developed others, principally for aircraft work, such as the tubular rivet, the De Bergue rivet, etc. Established rules used in designing riveted joints in boiler and structural work are unsatisfactory when applied to thin sheets and break down entirely when applied to sheets below say 22 S.W.G. (0·028 in.). Dimensions of highly stressed riveted joints in thin sheets are always based on actual tests. Under this state of affairs aircraft designers required new rivets which would give a highly efficient joint, and two types, viz. the tubular and the De Bergue rivet, are largely used nowadays on aircraft work.

TYPES OF RIVETS IN COMMON USE.



TYPE	DIA. OF HEAD A	DEPTH OF HEAD B	RADIUS OF HEAD R	DEPTH OF POINT C	DIA. OF POINT E
1. SNAP (OR ROUND) HEAD	1·75	0·75	0·885	–	–
2. PAN HEAD	1·6	0·7	–	–	–
3. MUSHROOM HEAD	2·25	0·5	1·516	–	–
4. FLAT HEAD	2·0	0·25	–	–	–
5. C'SK. HEAD 60°	1·75	0·65	–	0·4	0·79
6. C'SK. HEAD 90°	2·0	0·5	–	–	–
7 C'SK. HEAD 140°	2·75	–	–	0·4	0·79

Fig. 147. Typical B.S.I. Rivets up to ½ in. Diameter

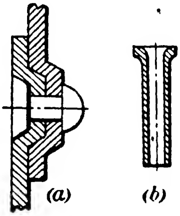

(a) (b)

Fig. 148

(a) De Bergue rivet
(b) Tubular rivet

Tubular Rivets. These give a higher efficiency than ordinary rivets. Special riveting machines have been developed for their use. (See Fig. 148 (*b*).)

De Bergue Rivets. The De Bergue patent rivets have the great advantage that the shear stress is entirely removed from the rivet shank, and it is distributed over a considerable surface of the sheets themselves. It also has another great advantage, viz. there is no projecting rivet head. (See Fig. 148 (*a*).)

Inspection of Riveted Joints. The inspection of riveting in aircraft work is most important. Unless close process inspection is made of the parts to be riveted, i.e. the drilling and general preparation of plates, etc., a good joint cannot result. The actual riveting operation, too, requires supervision. The external appearance of the joint is to some extent a good guide but it is recommended that specimen joints be sectioned so that the internal appearance of the joint can be examined also. Punching of rivet holes is permitted only in certain cases for it is liable, far more so than drilling, to burr and "drag" the plates. Burrs must be removed from the sharp edges of the holes and swarfe and chips removed from the surfaces of the work. Heads of rivets must be free from cracks or flash edges, they must be of good symmetrical shape, well closed down to the surface of the work. Rivet bodies must well fill the holes and be straight.

Some typical faults are shown, exaggerated, in Fig. 149, (*a*) head and plate damaged by hammer blow, (*b*) rivet, too long, causes flash of surplus metal, (*c*) unsymmetrical head, (*d*) bent rivet due to mal-alignment of holes (*e*) separated plates, rivet spewed between them.

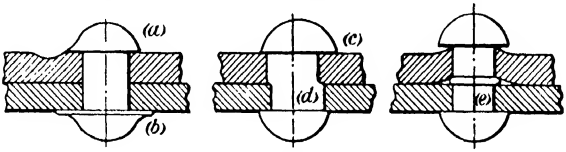


FIG. 149. TYPICAL FAULTS

When two parts through which either a torque or a suddenly applied load has to be transmitted it is essential to inspect the joints most carefully. Loose or badly fitted rivets used on such joints would readily shear. Rivets should be a good and complete fit in the holes which should be jig drilled to close limits.

It is also essential that rivets be of the material and in the condition specified. In this connexion it should be mentioned that Inspection Leaflet No. 426 deals at length with the control of heat treatment of **duralumin rivets,** which may be used only in the finally heat-treated condition. Age hardening of these rivets renders satisfactory closing impracticable. Therefore detailed instructions have been issued on the control of duralumin rivets from the time of their issue from the stores until they are actually incorporated in the aircraft structure.

Free Advisory Service on Welding. A series of illustrated booklets called *Welding Memoranda* is issued free to firms using welding equipment. Memorandum No. 7 is *Inspection of Arc Welded Work.* These memoranda are obtainable from: The Advisory Service on Welding, Ministry of Supply, Great Westminster House, Horseferry Road, London, S.W.1.

TESTING AT LOW TEMPERATURE

Tests for Aircraft Instruments. Aircraft operating at high altitudes calls for tests of instruments and equipment at correspondingly low temperatures.

Air Ministry specify varying temperatures, according to the purpose of the equipment and its location on the plane. Test temperatures down to minus 60° C. are required, sometimes followed by high temperature tests up to plus 60° C.

Special cabinets, of varying design, all fitted with special multipane windows, giving clear vision to instruments and thermometers during tests, are now in general use by the leading manufacturers of aircraft instruments.

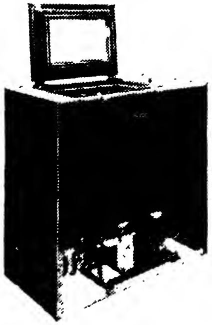


FIG. 150. KELVINATOR LOW TEMPERATURE TOP-ENTRY TESTING CABINET

For watches, clocks, gunsights, etc.

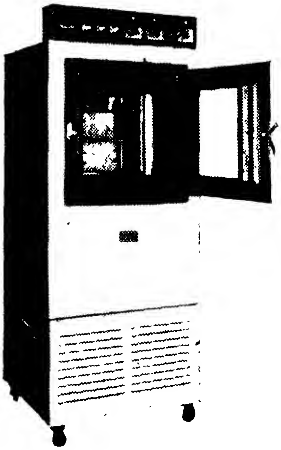


FIG. 151. KELVINATOR LOW TEMPERATURE CABINET: VERTICAL, SINGLE-COMPARTMENT MODEL

For all types of aircraft instruments, dry batteries, magnetos, etc.

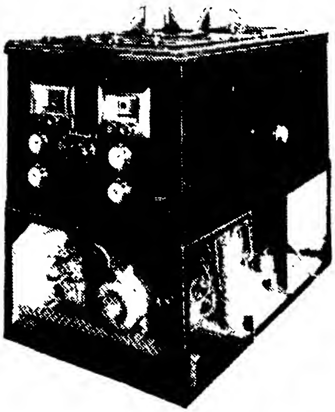


FIG. 152. KELVINATOR LOW TEMPERATURE MULTI-TYPE TEST CABINET

Two or more compartments, each independent with high or low temperature.

Duralumin—Rivets, Sheets and Blanks. To maintain ductility after heat-treatment, it is necessary to hold duralumin at low temperature. It hardens after 1½ to 2 hours at atmospheric temperature, and has to be re-softened by further heat-treatment, *calling for very careful supervision by Inspection Department* to ensure that all material is returned, and fresh supplies issued, at two-hourly periods. If maintained, however, at minus 15° C. ductility is retained for a period of seven or eight *days*. With a higher temperature of, say, minus 6° C.

the period is lessened to three days, and at 0° C. the permissible period is only twelve hours.

Aeroplane factories now use specially designed bench (or transportable) boxes for rivets and blanks which hold details at minus 15° C. and maintain the necessary ductility with no further heat-treatment. *Idle periods for presses and operators, and the labour involved in collection and redistribution are eliminated. The resultant quality and output are constant, and the load on the heat-treatment plant is less and regular.*

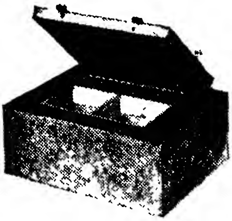


FIG. 153. KELVINATOR BENCH BOX FOR DURAL RIVETS

Various designs for operations or transport. (Patented.)

Each bench box has a thermal insert containing a eutectic solution which is frozen solid in a freezing cabinet. Inserts are changed only at 12-hour intervals.

Shrink Fits by Low Temperature. Considerable difficulty has been experienced in fitting the numerous bushes needed in the casings of light alloy used in the construction of *aero engines.* These casings are liable to distortion or other damage if heated, and further, insertion of the bush by pressure tends to either distort these light bushes, or to scrape metal from the softer casing, so reducing the "interference" and grip. Bushes have become loose in operation, and ejection tests in many cases show a heavy reduction in the estimated resistance.

By chilling the bushes sufficiently, ample shrinkage is obtained, and the bushes can be tapped home with a light rubber hammer, with the casing at atmospheric temperature. There is no distortion or shaving, and all the calculated grip by interference is obtained.

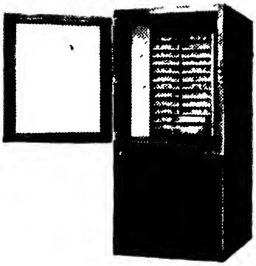


FIG. 154. KELVINATOR CABINET FOR RE-FREEZING THERMAL INSERTS FOR BOXES

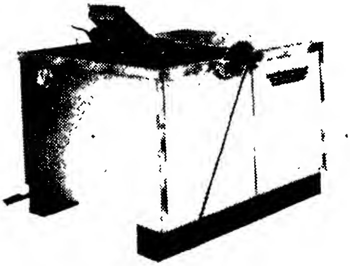


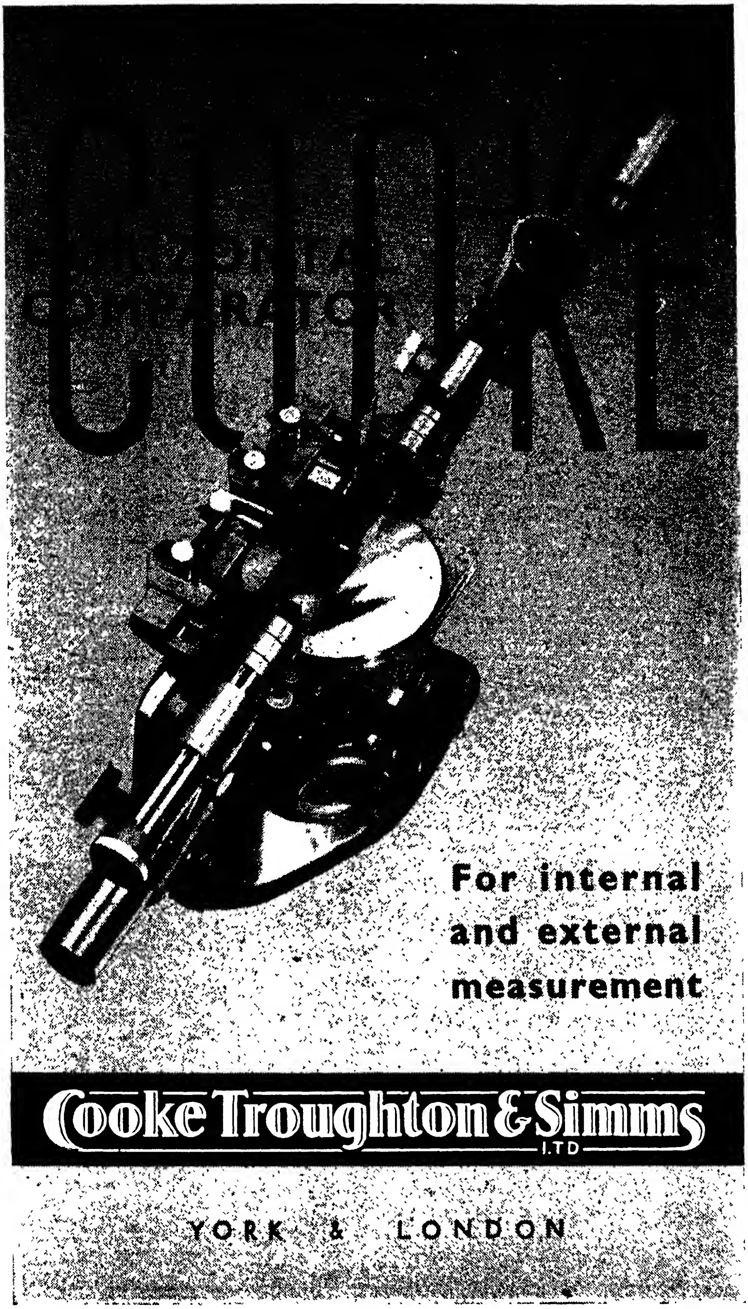
FIG. 155. KELVINATOR CABINET FOR LOW TEMPERATURE SHRINKAGE AT MINUS 72° C. (−98° F.)

1¼ h.p. fully automatic plant. Self-contained

Previously the interference allowance was excessive and defeated its own object. Better results are now obtained by this new method, using less interference.

Outer races of roller and ball bearings, sleeves, liners and even breech blocks of guns are being dealt with satisfactorily in this manner.

INDEX



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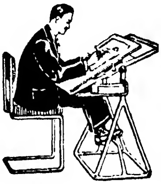

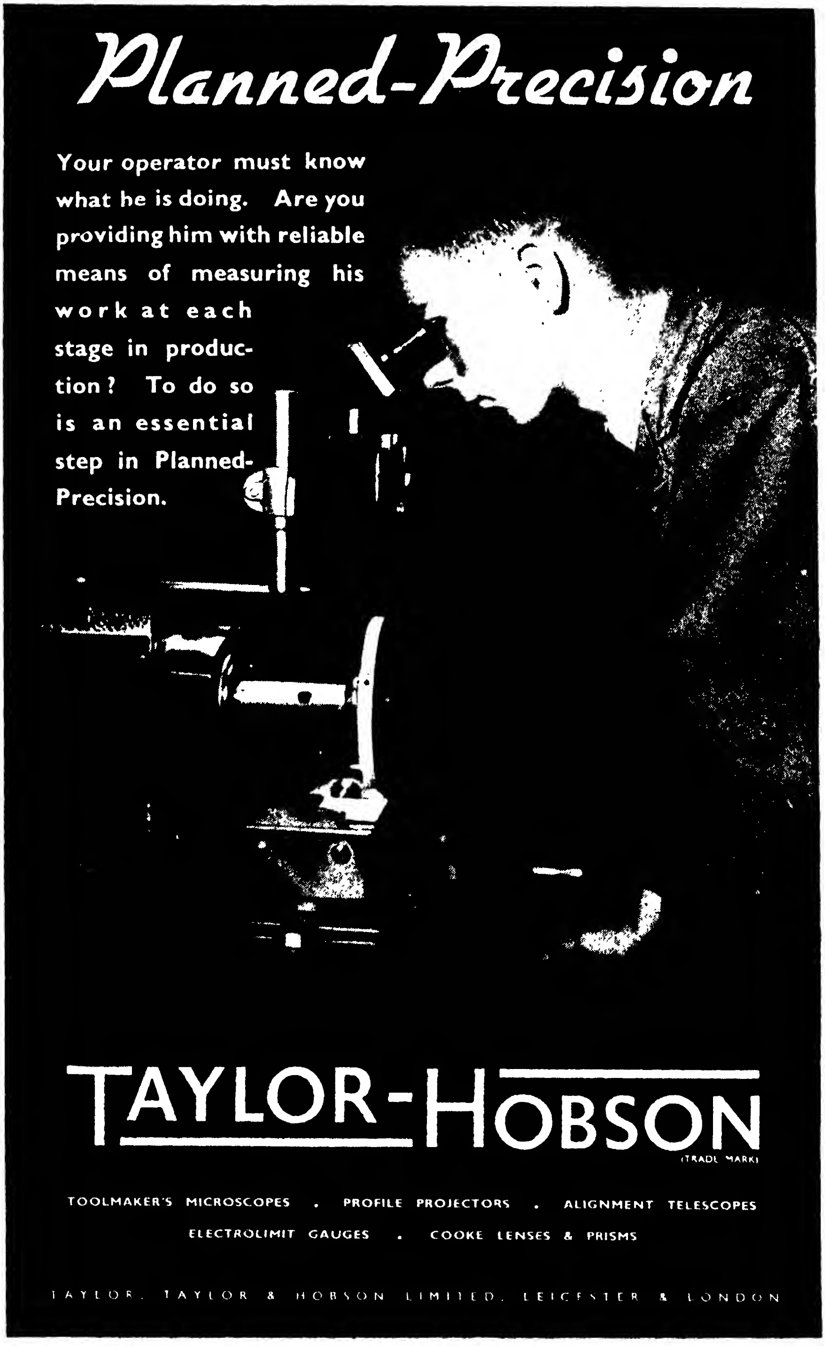

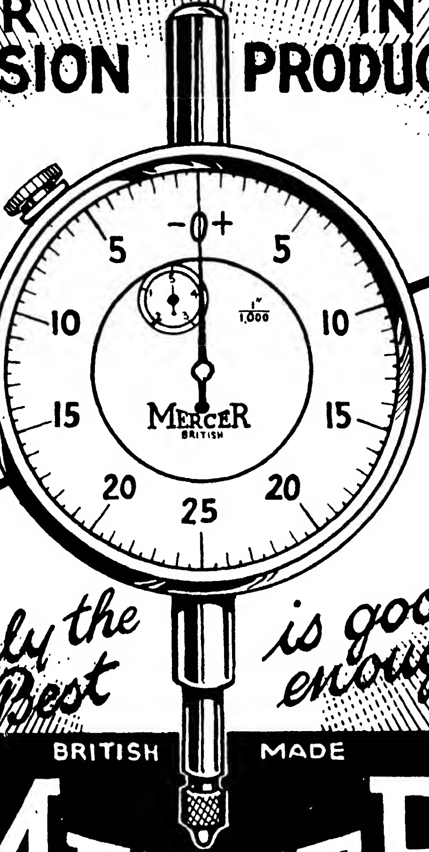
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